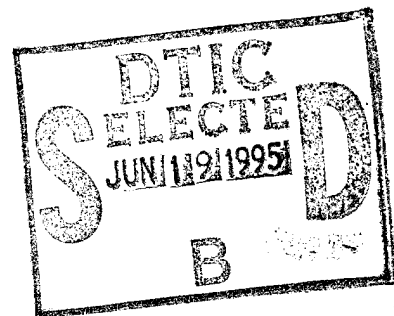# NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A SURVEY OF RESEARCH IN HELICOPTER HIGHER HARMONIC CONTROL WITH PLANS FOR NEARTERM NAVAL POSTGRADUATE SCHOOL TESTS

by

Jeffrey H. Carlsen

March 1995

Thesis Advisor: E. Roberts Wood

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A survey of research in the area of helicopter vibration reduction through the use of higher harmonic bade pitch control is presented. Higher Harmonic Control (HHC) is an active vibration suppression system for helicopters. Vibration is reduced through feathering of helicopter rotor blades at $(b-1)\Omega$, $b\Omega$, and $(b+1)\Omega$ harmonic relationships to reduce airframe vibrations at the blade passage frequency $b\Omega$ where b is the number of blades and Ω is the main rotor rotational speed. Research has been in the areas of blade stresses, vibrations, control systems HHC algorithms, and methods of actuation. HHC has also been reported to affect helicopter performance and main rotor noise.

Also presented are preliminary plans for performance testing testing of a Higher Harmonic Control system by the Naval Postgraduate School on the U.S. Naval Academy whirl tower at Annapolis.

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A survey of Research
in Helicopter Higher Harmonic Control
with Plans for Nearterm Naval Postgraduate School Tests

by

Jeffrey H. Carlsen
Lieutenant, United States Navy
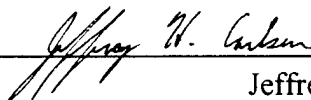B.S., Kearney State College, 1986

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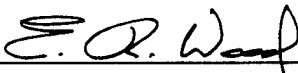MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

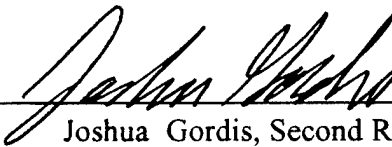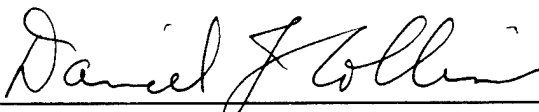from the

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March 1995

Author: _____
Jeffrey H. Carlsen

Approved by: _____
E. Roberts Wood, Thesis Advisor

_____
Joshua Gordis, Second Reader

_____
Daniel J. Collins, Chairman
Department of Aeronautics and Astronautics

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ABSTRACT

A survey of research in the area of helicopter vibration reduction through the use of higher harmonic blade pitch control is presented. Higher Harmonic Control (HHC) is an active vibration suppression system for helicopters. Vibration is reduced through feathering of helicopter rotor blades at $(b-1)\Omega$, $b\Omega$, and $(b+1)\Omega$ harmonic relationships to reduce airframe vibrations at the blade passage frequency $b\Omega$ where b is the number of blades and Ω is the main rotor rotational speed. Research has been in the areas of blade stresses, vibrations, control systems, HHC algorithms, and methods of actuation. HHC has also been reported to affect helicopter performance and main rotor noise.

Also presented are preliminary plans for performance testing of a Higher Harmonic Control system by the Naval Postgraduate School on the U.S. Naval Academy whirl tower at Annapolis.

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I. INTRODUCTION

A.   GENERAL

Oscillating air loads are the primary source of helicopter vibrations. These oscillating air loads are created by variations in rotor blade velocity and angle of attack as the rotor blade changes its orientation to oncoming air. In steady-state forward flight, the rotor blade encounters changing air loads during each rotation. A primary contributor to angle of attack changes is the variation in the downwash (inflow) encountered by the blade during each revolution. Blade excitation in steady-state flight is the periodic in 2Π per revolution and therefore occurs at harmonics of rotational speed. Blade dynamic response in turn leads to shears and moments that are transmitted to the blade root, then the shaft and finally the airframe.

Various methods have been tried to reduce or eliminate the vibrations of the airframe. For the most part, methods have been limited to vibration absorbers and vibration isolation systems. The primary shortfall of these methods for vibration reduction is their treatment of vibrational loads only after they have been introduced into the airframe. Because of this, these methods are referred to as passive means of vibration control. These methods have been only partially successful in reducing helicopter vibrations. They have also imposed significant weight penalties. In the case of the Navy's SH-60B there are three fixed tuned absorbers at about 70 lbs. each and four bifilar absorbers at about 40 lbs. each for a total weight penalty of 370 lbs. In contrast, Higher Harmonic Control, the subject of this thesis, is an active vibration suppression system

that eliminates the vibrations at the source, the rotor. This is done by altering the

aerodynamic loads on the rotor through high frequency feathering of the rotor blades at

small angles (less than 1 degree) at frequencies that are integral harmonics to the

imposed vibrations. In effect Higher Harmonic Control senses and cancels the

vibrations. This active vibration control method has demonstrated up to 90 percent

reductions in airframe vibrations.[Ref. 1]

B.   STATE OF HELICOPTER VIBRATION

As shown in Figure 1, vibration levels have been greatly reduced since the early

days of helicopter flight, but they are still considerably higher than those of a fixed wing

aircraft. Typical helicopter vibrations are currently in the range of .1g. Fixed wing aircraft

vibrations are approximately 0.02g. The largest helicopter vibrations occur at the lowest

blade number multiple times rotor rotational speed, typically the 10-20 Hz range.

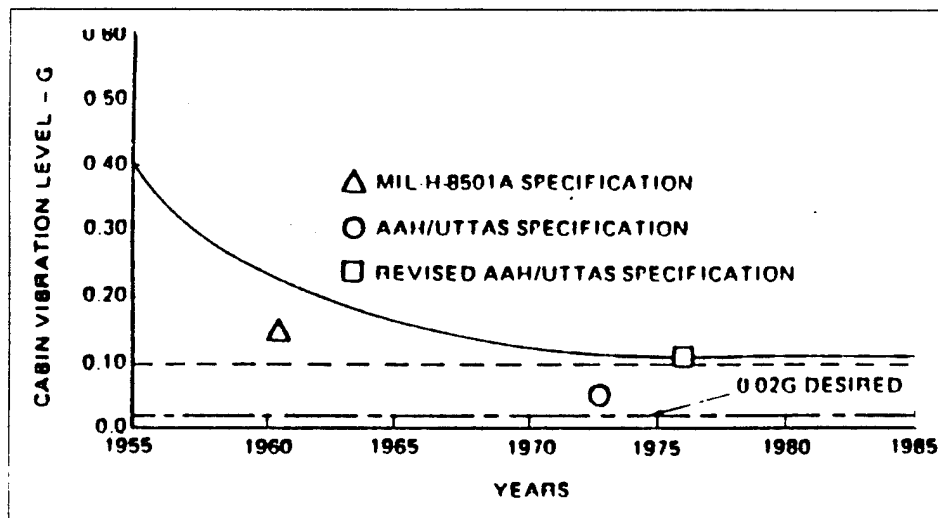Overlapping this is the range of maximum human discomfort, 3-12 Hz. [Ref. 2,3]

Figure 1. Trend in helicopter vibration. [Ref. 2]

Attempts have been made to reduce helicopter vibrations further. During the AAH/UTTAS (Apache and Blackhawk,) procurement program, the Army set the vibration level goals at 0.05 g's. This goal was found to be unobtainable by the technology available at the time, and the Army was required to increase the allowable vibration levels to their current levels. [Ref. 2]

C.   THE NEED FOR VIBRATION REDUCTION

Vibration has many adverse effects on helicopters. Some of these effects include increased stresses on dynamic components, decreased component life, decreased fatigue life, increased maintenance time, reduced reliability of components, more inaccurate weapon systems, and discomfort of crew and passengers. If levels are too high, controlled tests [Ref. 4] have shown that after a given time, crew proficiency begins to degrade.

Overall, additional problems caused by high vibrations in helicopters lead to higher operating costs. It is evident that a substantial reduction in vibration would be a great benefit to helicopter aviation.

D.   VARIOUS NAMES FOR HIGHER HARMONIC CONTROL

The technique of using high frequency blade feathering to reduce vibration has several different names. These include Higher Harmonic Control, Higher Harmonic Pitch Control, Muticyclic Control, Vibration Reduction through Control Feedback, Second Harmonic Control, and Individual Blade Control. All of these but one work on the same

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basic principle. Individual Blade Control however, implies a somewhat different system. For clarity, only the term Higher Harmonic Control, or HHC, will be used unless discussing Individual Blade Control which will be differentiated.

E.   HOW HIGHER HARMONIC CONTROL WORKS

A typical helicopter is controlled by varying the thrust magnitude and direction of the rotor system. The magnitude of the rotor's thrust is proportional to the rotor's coning angle. The direction of the thrust vector is perpendicular or normal to the plane described by the blade tips known as the rotor "tip path plane". Change in thrust magnitude and direction is accomplished by changing the angle of attack of the rotor blades. The angle of attack may be constant with the blade azimuth position as a blade rotates around the rotor mast, or vary with azimuth. Simultaneous or collective variation of angle of attack for all the blades at all azimuth positions is known as collective control. Changing the angle of attack as a function of azimuth is known as cyclic control. Cyclic and collective settings are relatively constant for steady state flight at a given airspeed. Higher Harmonic Control varies blade element angle of attack ,at a frequency equal $(b-1)\Omega$, Ω, and $(b+1)\Omega$. Illustrated in Figure 2 is the superposition of collective and cyclic control together with 4Ω, or 4P.[1] The combination of collective and cyclic variation, the amplitude and phase, as well as the effects on a rotor is discussed in the next chapter.

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[1] For helicopter rotors, oscillations occurring at integer multiples (n) of the rotor frequency are referred to as "n per rev" oscillations, or simply, "nP."
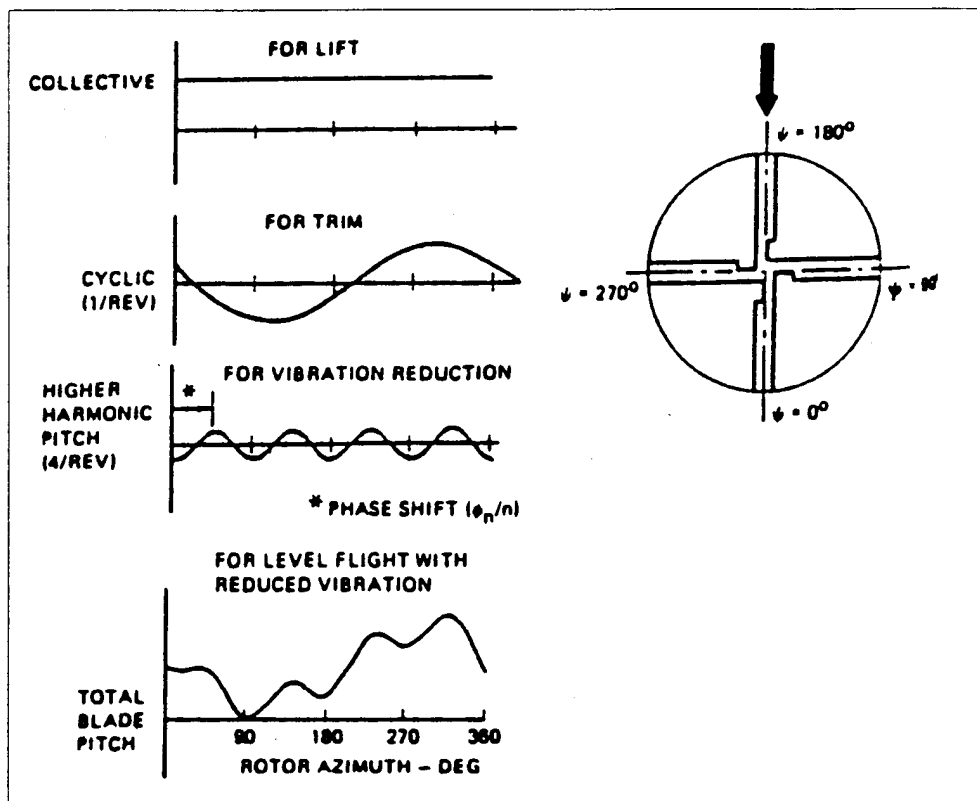
Figure 2. Collective, Cyclic, and HHC effects on Blade AOA [Ref. 1]

A typical Higher Harmonic Control system is composed of vibration sensors, accelerometers or strain gauges, and actuator system, a microcomputer, and an Electrical Control Unit.

F.   THE ROTOR AS A FILTER

Helicopter rotors have the interesting characteristic of acting as a filter for vibrations between the rotor and the fuselage. In flight, a rotor with N blades will transmit forces at frequencies of N-1, N, and N+1/rev. in the rotating system to the fuselage at N/rev. frequency. This assumes that the helicopter is flying in steady-state level flight. For example, on a 4 bladed helicopter,

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- 3P and 5P flapwise blade root shears result in 4P hub pitching and rolling moments in the fuselage.

- 4P flapwise blade root shears result in 4P vertical forces in the fuselage.

- 3P & 5P chordwise root shears produce 4P fore and aft forces in the fuselage.

- 4P chordwise root shears produce 4P yawing moments in the fuselage.

These relationships work similarly for 3, 4, 5, 6... bladed rotors. The rotor filtering also works in the other direction, that is, 4P pitching and rolling moments in the fuselage result in 3P and 5P excitations of the rotor, blades, etc.

G. INDIVIDUAL BLADE CONTROL VS HHC

The majority of helicopters flying today use a swashplate to control the pitch of the rotor blades both cyclically and collectively. This couples the inputs and reactions of each of the individual blades. The Kaman flap system similarly couples its blades through a hub swashplate assembly. For an Individual Blade Control system, each of the rotor blades may be, as the name implies, controlled individually. This is typically done through blade flaps or actuators in the rotating system. An Individual Blade Control system has freedom to independently control blade pitch. Unconstrained by the swashplate, it is, however, more complicated, and best achieved by a fly-by-wire system.

II. SURVEY OF HIGHER HARMONIC CONTROL

A.   SCOPE

Since the successful HHC flights of the 1980's by Hughs/McDonnell Douglas (OH-6A) followed by Sikorsky (S-76) and Aerospacial (SA-349), the number of research papers on this topic has grown very rapidly. This includes both U.S. and foreign papers. It is the aim of this survey to scope the status of Higher Harmonic Control to date. Included is a summary of major contributions in the development of Higher Harmonic Control. The survey is focused on studies leading toward flight testing, and significant developments since flight testing was concluded. In the course of researching for this thesis, more articles were reviewed that could be included in the text of the thesis. These are listed in the Appendix for additional reference.

B.   SURVEY OF HIGHER HARMONIC CONTROL

The first documented investigator of Higher Harmonic Control was Stewart in England [Ref. 5] in 1952. He conducted an analytical investigation of application of 2P feathering to increase rotor performance. Stewart proposed using second harmonic pitch to postpone the rotor performance limitations due to retreating blade stall. Stewart's idea was to vary pitch input with blade azimuth position, resulting in increased lift fore and aft on the rotor disc and decrease lift to the sides. The effect would be to sustain thrust at higher advance ratios or increase thrust at a fixed advanced ratio. Stewart noted that local angle of attack changes and pitch changes would not be the same as the pitch variation.

The flapwise blade motion would be making a secondary angle of attack contribution that was dependent on radial location. This secondary contribution changes the local inflow angle. Stewart's work did not account for angle of attack changes over the disk due to wake vorticity. Modeling blade motion by rigid flapping and neglecting wake vorticity changes, Stewart was able to determine the relationship between the second harmonic pitch and the angle of attack change at every point on the disk. This model allowed Stewart to obtain a relationship between second harmonic pitch input and angle of attack. The relationship also showed that the second harmonic pitch input leads the angle of attack by about 40 degrees. This relationship may be used to estimate the amplitude and phase of the second harmonic pitch required to eliminate stall in any flight condition. [Ref. 3]

In 1961, Arcidiacono [Ref. 6] extended Stewart's analysis and examined angle of attack variation at the blade tip and the magnitude and phase of the second harmonic pitch which avoids retreating blade tip stall as long as possible. Arcidiacono noted that tip stall could be delayed to even higher advance ratios by second and third harmonic pitch combined, and presented numerical results for the obtainable increase in maximum advance ratio. This increase was calculated to be approximately 25 percent. Arcidiacono did not calculate the effects that second harmonic pitch control would have on vibratory root forces. [Ref. 3]

Under contract from the Army transportation research command Bell Helicopter used Stewart's and Arcidiacono's investigations as a base reference and undertook flight

tests of second harmonic pitch on a two bladed UH-1A rotor in 1962. Results of the

investigation are reported by Wernicke and Drees [Ref. 7] and by Bell Helicopter [Ref. 8]

These tests were made possible by the company's invention of a simple rotor head

mechanism to create second harmonic pitch with adjustable amplitude and phase. This

mechanism is shown in Figure 3.
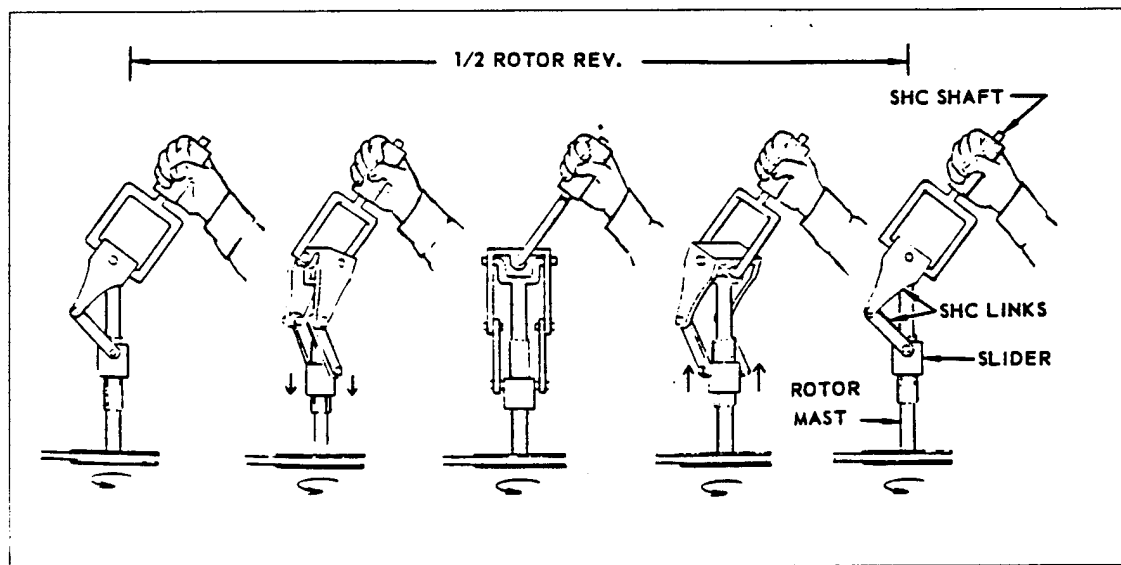
Figure 3. Schematic of second harmonic control actuation device. [Ref. 7]

To measure the effectiveness of the system, measurements were made of blade air

loads and bending moments at several radial stations, oscillatory loads in both the

conventional and second harmonic parts of the pitch variation mechanism, loads

transmitted from the rotor to the fuselage, vertical vibration at three fuselage locations,

and standard performance data. The UH-1A tests were aimed at vibration reduction, not

at elimination of retreating blade stall. [Ref. 7]

Analysis showed that profile power rose enough due to increased angle of attack at

the fore and aft blade position to counter the drag reduction at the retreating and

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advancing blade position. Acidiacono [Ref. 6]and Stewart [Ref. 5] did not expect a power

reduction, their aim was postponement of speed limitation due to retreating blade stall.

[Ref. 7]

Some vibration reduction was achieved as predicted, however the tests also

showed some complex relationships which were difficult to explain. No second harmonic

pitch adjustment was found which completely eliminated second harmonic vertical

vibration at any one of the points being measured on the fuselage. Vibrations could be

reduced a bit at each point by various phased pitch adjustments, but decreases at some

locations often resulted in increases at others. Increased blade and control loads were also

measured with decreases in vibration. Some of these loads were significant. The best

results were achieved near the center of gravity of the fuselage. At this location vibration

could be reduced by more that 50 percent while reducing blade and control loads by the

same amount. Vertical vibrations are shown in Figure 4. [Ref. 7]
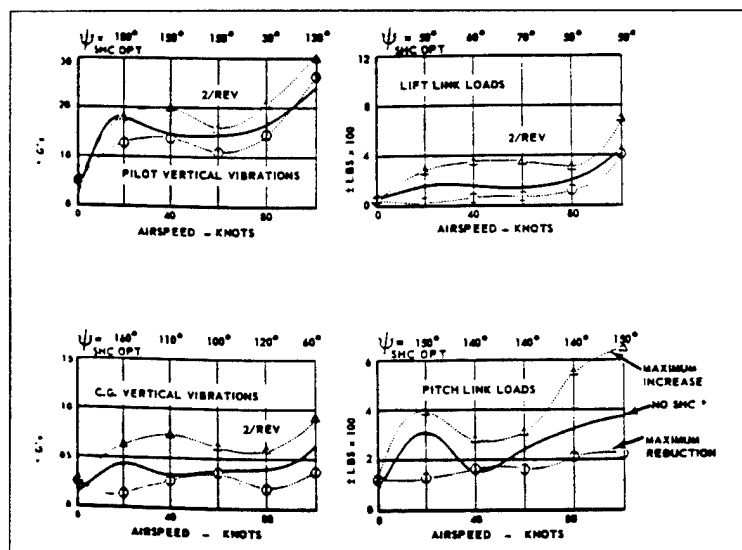
Figure 4. Second Harmonic Control Vibration Reductions. [Ref. 7]

A relation between vibration reduction and shaftwise hub force reduction was not found. Oscillatory shaftwise force amplitude and vibration changed in opposite directions for most phasings of second harmonic pitch input. In plane harmonic hub load measurements, which could account for these trends, were affected very little by the second harmonic control inputs. The control system loads which were transmitted to the fuselage were of the same order as the reductions of the oscillatory hub forces. It was theorized that these two forces were in effect canceling each other out for the total effect on vibration. It was suggested that conditions where vibrations were reduced were those where hub and control force changes had a net beneficial effect. No analysis was conducted to determine the size of the control force influence on fuselage vibration. [Ref. 3]

The final observation of the Bell report was that, when second harmonic pitch was adjusted to decrease the second harmonic aerodynamic root force, the net second harmonic root force increased. This was the first indication that Higher harmonic pitch and aerodynamic root forces cause significant changes in inertial root forces as a result of changes in harmonic blade motion. [Ref. 3]

Wernicke and Drees concluded from the flight tests that more study and analysis was required before Higher Harmonic Pitch control could be made useful. The results were so complex that investigations were discontinued until a practical system of harmonic pitch could be designed. [Ref. 7]

In reference to the Bell two bladed rotor control forces Mard [Ref. 9] made the observation that control loads do not appear to be the same problem on multi-bladed helicopters as they are on two-bladed configurations. The magnitude and frequency content of these loads on the two bladed rotor make it necessary to attenuate their effects even at low advance ratios.

In 1965 Boeing made an investigation into higher harmonic pitch control. A computer program was then available that could calculate the nonuniform induced velocities over the disk from the prescribed vortex wake of the rotor. This permitted the calculation of vibratory root forces with improved accuracy. In this program, third harmonic pitch was used to estimate the pitch amplitude required to eliminate third harmonic shaftwise root forces on one of Boeing's three bladed rotors. They estimated the amplitude to be about two degrees. The analysis included several approximations of only moderate accuracy, but the results were a good estimate. Importantly, they showed a large increase in blade flapwise bending moments due to the pitch adjustments which eliminated root forces. [Ref. 3,11]

In 1967, Shaw [Ref. 3] made an analytical investigation, like the Boeing investigation [Ref. 10], into the effect of third harmonic pitch on the vibratory hub forces of a three bladed rotor. This work was conducted with the use of a new computer program that calculated unsteady rotor air loads including the effects of shed vortices. In this investigation, a single flight condition was considered, level flight with u=0.2. Shed vortices were found to have a small but not negligible effect on higher harmonic pitch

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effectiveness. Phase-dependent summation of aerodynamic and inertial forces at the blade root, and their effects on higher harmonic pitch were the primary focus of this study. The investigation showed elimination of third harmonic shaftwise root forces by third harmonic pitch requires mutual cancellation of the third harmonic aerodynamic and inertial forces. Partial spanwise pitch control was proposed as a method for obtaining a better relation between aerodynamic and inertial root force increments. This would allow reduction of aerodynamic and inertial forces amplitudes while causing their cancellation, while not increasing their amplitudes. It was also observed that elimination of third harmonic shaftwise root forces had only a small effect on the third harmonic longitudinal in plane forces, as would be expected since the in-plane forces are primarily a function of in-plane 2P and 4P forces. [Ref. 3]

Another analytical investigation was published by Daughaday, also in 1967 [Ref. 11]. A computer program was used to calculate unsteady rotor airloads induced by the vortex wake. The program was similar to that used by Shaw, but allowed for complete adjustibility of pitch both radially and azimuthally. Daughaday studied the simultaneous application of a set of even numbered pitch harmonics to a two bladed teetering rotor at three advance ratios. Two different problems were solved. For the first problem, the amplitudes and phase were calculated for the pitch harmonics which would eliminate a given set of even numbered shaftwise forces. Elimination of the second and fourth shaftwise harmonics were found as well as a solution for the second through twelfth harmonic shaftwise root forces. The mathematical model made the calculations of the

root forces above the third harmonic very inaccurate. This was due to limitations in the mathematical model in the areas of wake geometry and blade vortex interaction aerodynamics. The results showed some qualitative physical effects that may occur. Daughaday's study solved for complete elimination of unsteady lift from the rotor blades in forward flight. The solution requires complete adjustability in pitch both in azimuth and radial location. The complex requirements for blade twist make this very impractical. Interestingly though, pitch requirements above second harmonic were generally less than one degree and often smaller. This would later be confirmed by flight test [Ref. 2] For the second problem, a solution was found for the elimination of even shaftwise root forces at three advance ratios. The solution found three noteworthy effects. First, there were moderate harmonic interactions. One harmonic input effected others. Second, cancellation of some harmonic aerodynamic-inertial root forces required an increase in both of these forces. Third, as the advance ratio changed, so did the pitch control requirements. [Ref. 3]

An analysis similar to Daughaday's was conducted in 1969 by Balcerak and Ericson [Ref. 12]. Additional elements in Balcerak and Ericson's analysis were two torsion modes, chordwise in plane forces, rotor drag and torque. Results were similar to Daughaday's with two additions: torsional response can be significant if pitch frequency is applied near the torsional natural frequency, also torque and drag may be increased 20 percent under certain pitch harmonic conditions. [Ref. 3]

The first wind-tunnel experiments on a Higher Harmonic Control system were conducted by McCloud and Kretz from 1971 to 73 [Ref. 13, 14, 15]. These tests were conducted in the NASA Ames 40x80 wind tunnel with a 40' diameter, two-bladed, Dorand DH 2011 Jet Flap (Teetering) Rotor. The control system used was actually an Individual Blade Control system, which is differentiated from Higher Harmonic Control in the first chapter. The experiments were designed to support research leading to a helicopter design not having a swashplate plate. Kretz refers to this as a "Control Configured Vehicle." Kretz notes that it is the swashplate itself that imposes the most stringent limitations to rotor control by coupling the blades and imposing monocyclic pitch variation. The tests were able to show 40 percent reduction in blade stresses and 48 percent reduction in vibration at an advance ration of 0.4. Because the rotor tested was a jet flap, blade element angle of attack values required to implement Higher Harmonic Control were not measured. [Ref. 13]

A significant development in these wind tunnel tests was the use of matrix calculus to replace the mathematical model previously used to express the control pitch inputs. A suitable mathematical algorithm model for jet flap rotors was difficult to develop. To simplify the handling of a large number of parameters, the matrix equation,

$$Z = Z_o + T * \Theta \qquad\qquad (1) \text{ [Ref. 13]}$$

was used, were Z is the output vector, consisting of vibrations or blade stresses as desired, Z_O is the state of the rotor without Higher Harmonic Control, Θ is the Higher

Harmonic Control input pitch vector, and T is the coupling matrix representing the rotor

and fuselage. The vectors Zo, and Z typically consist of six elements, the sine and cosine

portions for three vibration forces such as Fx, Fy, and Fz, Θ is a six element vector

containing the sine and cosine of the three input oscillations, collective, fore-aft and

lateral for the swashplate. In this linear model, the elements of the T matrix are 'influence

coefficients' which relate input to output. The wind tunnel testing conducted identified

influence coefficients for over 30 different test conditions at an advance ratio of 0.4,

inputting second, third and fourth harmonic flap deflections individually. In some flight

conditions it was found that reductions in blade bending moments caused increases in

vibration, and conversely vibration reductions lead to increased bending moments. Overall

it was shown that it was possible to keep the retreating blade out of blade stall in any flight

condition. [Ref. 13]

Interestingly, Kretz found the T matrix was practically insensitive to widely

varying flight conditions [Ref. 13]. In later studies, this was not found true for most rotor

systems with a conventional swashplate for control of blade pitch.

The first wind tunnel tests conducted on a conventional four bladed rigid rotor

with Higher Harmonic Control were presented in the fourth report of a series tests on a

7.5 foot rotor, conducted in the NASA-Ames 7x10 wind tunnel. The first tests, by

Kuczynski, et al. [Ref. 16] were conducted to determine rotor response to steady

swashplate and rotor angle of attack inputs from hover conditions to advance ratios of

μ=2.15. The second tests, by Kuzynski, et al [Ref. 17] were to find rotor frequency

response to swashplate cyclic and collective oscillations at the previous test conditions.

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The third tests, by Kuzynski, et al [Ref. 18], were conducted at similar conditions as the first two, but the rotor was subject to shaft pitch and roll oscillations, then the tests were repeated with a slightly less stiff rotor. The fourth tests, by London et al, [Ref. 19] consisted of expanding the data bank for higher lift levels, and the effects of Higher Harmonic Control. London et al, [Ref. 19] demonstrate how coefficients are found that relate to output vibrations to input excitation, either collective, cyclic longitudinal or cyclic lateral pitch, with two coefficients, gain and Phase lag. This investigation essentially found the values for the T matrix of Equation 1. Values for the gain ranged from 0.2 to 3 degrees. The input oscillations for the Higher Harmonic Control tests were all at 4P. Earlier tests involved testing with inputs of 3p, 4p, and 5p. [Ref. 19]

In 1975, McCloud [Ref. 20] conducted a theoretical study on a rotor employing a servo-flap to effect blade twist torsional deflections. The rotor analyzed was a unique product being developed by Kaman called the Controllable Twist Rotor. This rotor was four bladed, and had pitch actuation by both a conventional swashplate and control rod as well as a controllable flap on the outboard trailing edge. With this design the blades are elastically twisted by a trailing edge servo-flap which applies torsional moments to the blades, which in turn are reacted by the conventional root-end pitch controls. This is illustrated in Figure 5. [Ref. 20]

The study assessed the effects of multicyclic flap controls for 1P, 2P, 3P, and 4P excitations. The study was conducted in two parts. The first part calculated several

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performance and oscillating load parameters by a performance program. The second part

analyzed the results of the first part. [Ref. 20]
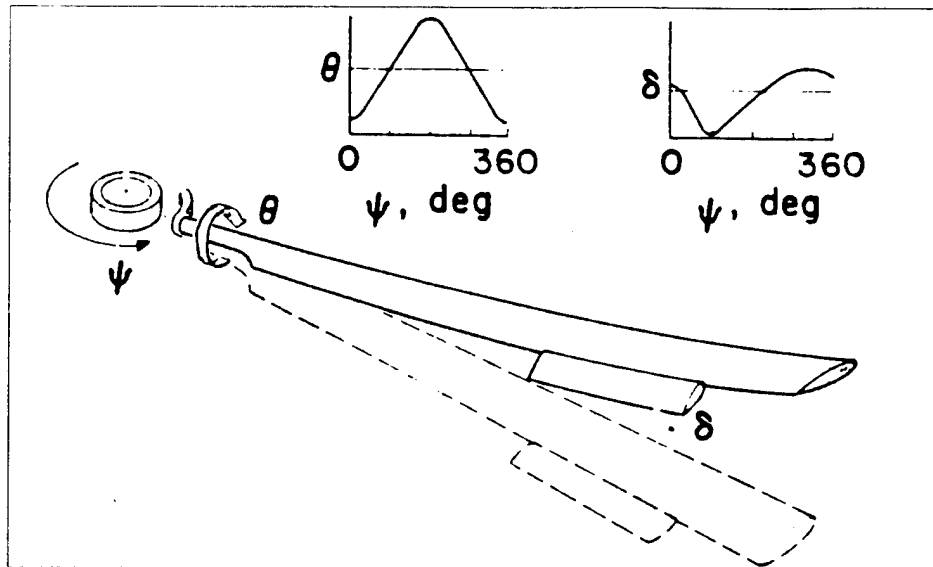
Figure 5. Kaman Controllable Twist Rotor. [Ref. 20]

The initial parameters found were generated by the use of a rotor performance

program written by Kaman Aerospace Corporation for analysis of this particular rotor

configuration. Inputs included gross weight, effective drag, dimensional characteristics of

the blade, as well as combinations of multicyclic control inputs of 1P, 2P, etc. Outputs

are the response of the rotor. The outputs of this program along with several of the

inputs, served as inputs for the next phase of analysis using the ROMULAN (ROtor

Multicyclic ANalysis) program. The ROMULAN program was based on the same idea of

using a matrix to model the rotor, that was used by McCloud and Kretz [Ref. 14] and

Kretz [Ref. 13, 15] in earlier tests .[Ref. 20]

Essentially, ROMULAN set up in input vector, f, consisting of flap angles inputs at various harmonics and phases, and output vector F, consisting of blade stresses, and solves for the coefficients in the matrix T.

$$[F]_n = [T]_{mn} x [f]_n \qquad \qquad \text{(2) [Ref. 20]}$$

Similarly, an output vector was defined with vibration levels as its entries. The two matrices were combined in a weighted equation and a value for the vector f, which minimized root mean square of harmonic stresses and vibration was found. [Ref. 20]

Good correlation was found when running the output vector back through the rotor analysis program. The results showed it was possible to achieve a complete elimination of pylon vibratory loads with a concurrent reduction in blade bending moments of 50 percent. It also found that required higher harmonic servo-flap deflections were on the order of 3 to 4 degrees. It is interesting to note that this process is roughly how later HHC flight programs would work, but more sophisticated. [Ref. 20]

Wind tunnel investigations were conducted by McHugh and Shaw on a four bladed hingeless rotor in 1975 and 1976 [Ref. 1]. The tests were conducted in the 20x20 Boeing V/STOL wind tunnel. The model was a 10 foot diameter, four bladed, soft in plane hingeless rotor. Importantly for the advancement of HHC, this rotor could be operated at near design tip speeds, giving data at an rpm where the relationship between blade modal frequencies and shaft speed harmonics was close to that of full scale rotors. [Ref. 1]

A significant aspect of these tests was the use of 4P harmonic oscillations for collective, lateral, and longitudinal cyclic motion of the swashplate fixed system to induce 3P, 4P and 5P pitch inputs to the rotor blades. On a four bladed rotor, major vibratory loads are controlled with 3P, 4P, and 5P blade pitch oscillations. The trigonometric relationships of a four bladed rotor head can be used to show that 4P rocking of the swashplate produces a combination of 3P and 5P blade pitch variations. If it is rocked about two perpendicular axes simultaneously, with the same amplitude, but phased 90 degrees apart, a pure 3P or 5P pitch will be produced depending on the direction of the phase difference. Put more simply, if the swashplate is whirled at 4p in one direction, 3p is produced, if it is whirled in the other direction, 5p is produced. This method was used in the testing to induce 3P and 5P oscillations. Vertical swashplate motion was used to induce 4P oscillations. [Ref. 1]

The tests were able to obtain a nearly linear relationship between blade and hub loads and harmonic inputs. An example of the relationships found is shown in Figure 5. In this figure A represents the magnitude and phase of the basic vibration, in this case 5p flapwise bending, the line B is the data collected, that is the magnitude and phase of the bending moment as a function of a fixed Higher Harmonic Control pitch amplitude at a given phase. C is a line representing the resulting 5p flapwise bending as a result of varying pitch amplitude and keeping phase constant. McHugh considers C somewhat radial, but a relationship can be clearly seen between the input amplitude and phase and the 5p flapwise bending. The testing conducted by McHugh and Shaw collected a large

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quantity of these types of plots for varying conditions. From these plots it is possible to

derive an approximate linear relationship between harmonic input and output, and then

solve for a value of pitch and phase that will cancel the type of vibration. For example,

Figure 6 can be used to solve for the value of pitch and phase for a 5p input to eliminate

5p flapwise bending moments. In this case about 0.15 degrees pitch amplitude at 300

degrees phase. McHugh and Shaw also showed that a reasonable approximation could be
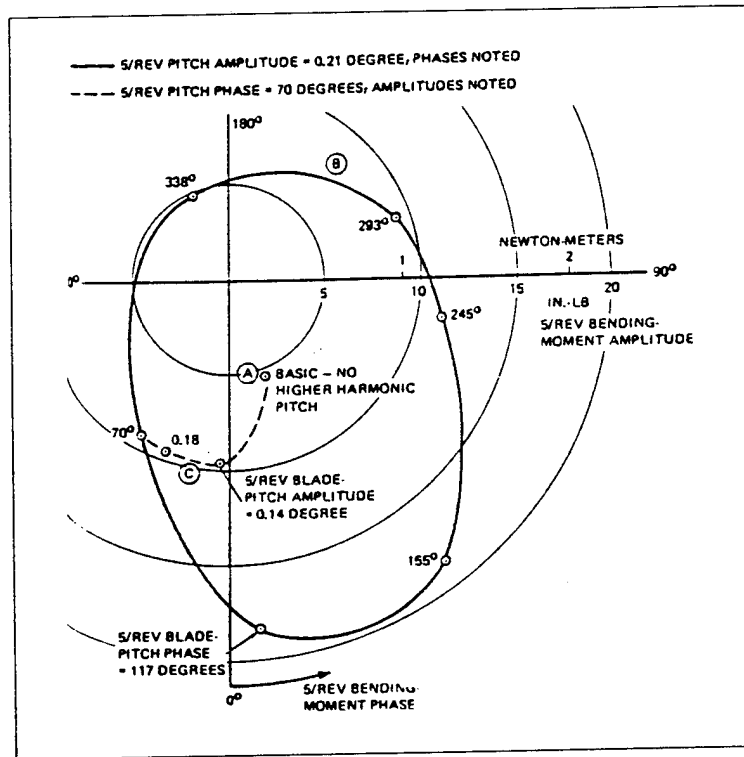
made with just one sample input. [Ref. 1]

Figure 6. 5P Flap bending moment at r/R=.11 for 5p blade pitch inputs at various amplitudes and phases at μ=0.3 [Ref. 1]

Another aspect of the testing was comparison of blade responses with that predicted by the Boeing Vertol Loads program. Correlation was excellent, and confirmed the expected reactions to harmonic input. This can be seen in Figure 7.
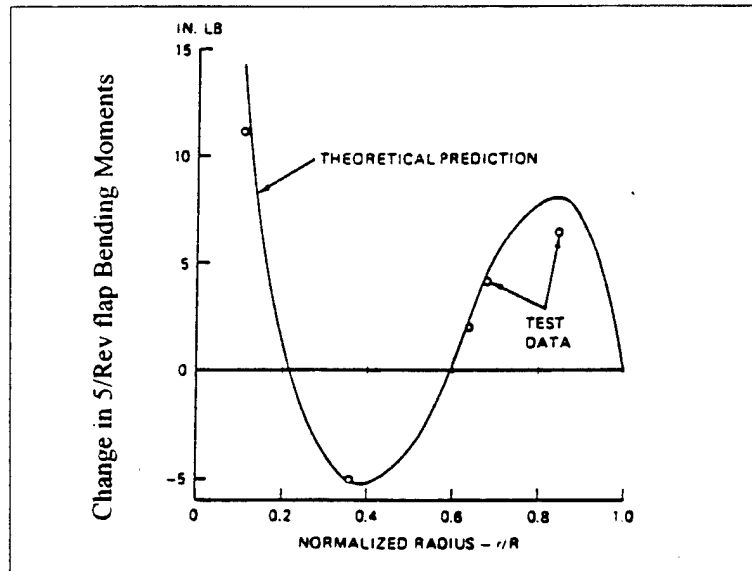
Figure 7. 5p pitch effects on blade loads- test data Vs theoretical prediction [Ref. 1]

Noting earlier work of McCloud [Ref. 20] and Kretz [Ref. 13], McHugh and Shaw pointed out the possible advantages of using a system of weighted averages between vibrational modes, and blade/hub loads. The system is essentially modern control theory used to minimize a cost function, but it was not referred to as such by McHugh and Shaw [Ref. 1]. The possible advantages of having both pitch root and servo flap control was also noted. The primary advantage of such a system would be the ability to reduce vibrations and blade loads at the same time, without any need to make trade-offs between the two. [Ref. 1]

The relationships between optimum input pitch angle and phase verses flight conditions (airspeed) were also calculated. These relationships may be seen in Figure 8. These relationships are significant, in that they determine how complex an in-flight controller will have to be. The relationships between the resulting moment and pitch input is different for each harmonic, and varied with flight condition. This information showed that in-flight adjustments of both pitch and amplitude will be necessary. Additionally, if pitch and phase remain constant throughout a flight envelope, the harmonic control may actually increase vibrations and loads in certain flight regimes. [Ref. 1]
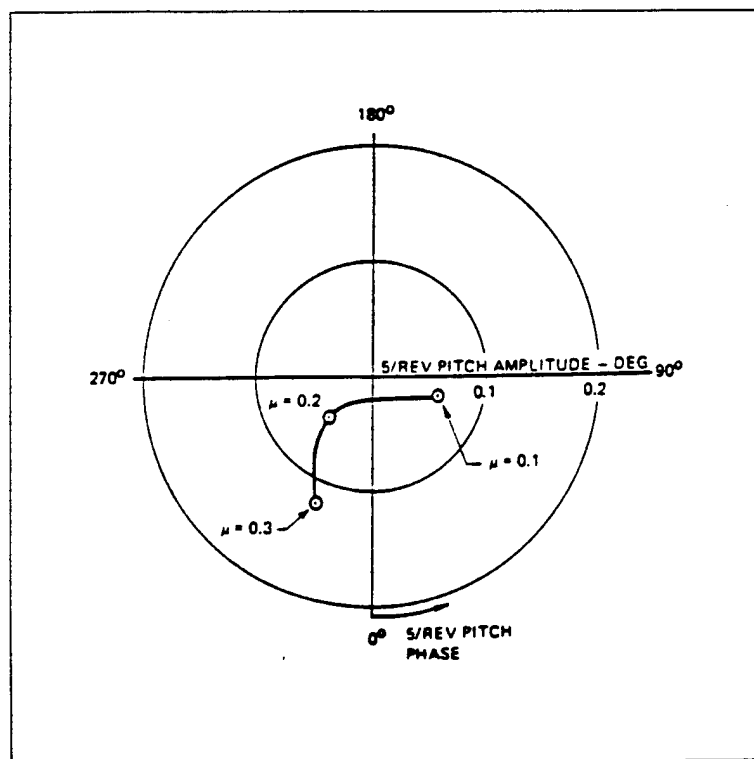
Figure 8. Effect of advance ratio in trimmed level flight on 5P pitch required to eliminate 5P root flap-bending moment [Ref. 1]

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The effects of higher harmonic control were noted to have minimal performance penalties, and there were frequently improvements. Some scatter of the data prevented any qualitative conclusions, and it was not further investigated. [Ref. 1]

The final results of the test showed:

- Reduction in hub loads did not cause significant blade loads or performance penalties.

- Required pitch inputs were generally less than 1 degree.

- Reductions of several vibratory components simultaneously was possible through superposition of inputs.

- In flight adjustments would need to be made for a real helicopter.

- The approximate pitch and phase for reduction of any vibratory component may be made from two trial inputs, one trial can give substantial reductions.

- State of the art (1975) theory accurately predicted blade pitching and torsional loads. [Ref. 1]

In 1977, Kretz [Ref. 21] conducted experimental and theoretical work exploring the feasibility of expanding the helicopter flight envelope through active feedback control, on a two bladed teetering system with individually controlled blades. Work was directed towards eliminating instabilities due to high advance ratios, avoiding stall conditions through pressure sensing, and suppression of aerodynamic disturbances. Work on this project was sponsored by DRME, the French government research agency. Kretz

describes his work in general terms. As of the publication date, the proposed system had not yet been fully tested, and only the analytical aspects were presented .

The rotor system used by Kretz placed the actuators in the rotating system. This eliminates the mechanical coupling of the swashplate and gives much greater flexibility in introducing oscillations into the rotor, but has a disadvantage. If directed solely at 4P vibrations on a 4-bladed rotor, control in the rotating system has the disadvantage that 3 frequencies (3P, 4P, and 5P) must be used where as a 4P input in the fixed system yields all three in the rotating system. As discussed in the introduction, this type of control is referred to as Individual Blade control, or IBC. The elimination of the coupling due to the swashplate provides greater flexibility on the ability to control a rotor and may be especially beneficial for transient flight regimes. An IBC system is a fly by wire helicopter, which has not yet been fully developed. [Ref. 21]

There are many design considerations for a control system for higher harmonic control of a rotor. Wind tunnel tests conducted by McCloud and Weisbrich [Ref. 22] in 1978 were aimed at analyzing some of the design tradeoffs that would have to be made for a practical system, specifically the type of algorithm to be used. The tests were conducted in the Ames 40x80 tunnel, again using the Kaman Controllable Twist Rotor mentioned earlier. Results of the tests confirmed earlier examinations such as those of McHugh and Shaw [Ref. 1], McCloud's earlier work with the same rotor [Ref. 20] and also with the jet flap rotor [Ref. 14]. Unique aspects of these tests were the stocastication of the returned data, the use of the program REGRESS, and Fast Fourier Transforms to resolve vibratory

components. The Stocastication of data eliminated the problem of "confounding," which causes the inability to distinguish which variable of interaction is responsible for what observed effect. REGRESS is a program, written by Kaman, that works similarly to ROMULAN, however it does not assume a linear relationship. Input and output for the program work the same way, and the output of the program provides the elements (influence coefficients) of the T matrix of Equation 1. From their work, McCloud and Weisbrich concluded the ROMULAN and the REGRESS algorithms were both accurate and useful, and Fast Fourier Transforms resolved data correctly. [Ref. 22]

In 1976, a joint project was undertaken by Hughes Helicopters, the U.S. Army, and NASA to systematically develop a flight-worthy Higher Harmonic Control system. (NASA Contract No. NAS 1-14552) Flight demonstration of the system on an OH-6A was the desired goal. To this end, Hammond [Ref. 23] first undertook wind tunnel tests of a 9 foot rotor in the NASA Langley 5 m Transonic Dynamics Wind Tunnel (TDT) with the goal of providing analysis and computer programs to sense and suppress vibratory excitation in either open or closed loop mode. In these tests the model was flown in Freon-12. This tunnel with Freon-12 as the fluid medium provided dynamically-scaled testing. It is the primary resource for scale flutter testing of all U.S. aircraft. After conducting single input, single output tests, like those conducted in earlier tests, the testing moved into multi-input multi-output testing. The SISO tests confirmed predicted results for blade loading, in plane, flapping and torsionally as well as required pitch angles. The model did have significant increases in 4P torsional loads, caused by the control rod

inputs, however, none of these loads were above the design limits. Of great importance was the NASA- Army substantiation of earlier HHC findings that required pitch inputs were small, i.e. 2 degrees or less. If required inputs were larger, Higher Harmonic Control would become impractical for an actual flying helicopter for two reasons: (1) Excessive power required for HHC and (2) High control loads and blade torsional loads. [Ref. 23]

Also analyzed were three different methods for determining optimum swashplate inputs for desired load and vibration outputs [Ref. 24]. The three techniques were the three point, Nonlinear (six-point) technique, and the two point technique. All three were shown to be effective. The matrix equations for the input and output were developed. Since there are three independent inputs, swashplate degrees of freedom, and six hub vibratory responses, the approach is to minimize just the three hub responses that contribute the most to vertical fuselage response, 4P vertical forces 4P fore-aft forces and 4p pitching moments at the hub. The transfer matrix shows that the inputs and outputs are fully coupled. This indicates inter-harmonic coupling must be adequately represented in the analytical model. Using data from the tests, the transfer matrix was found. Data collected was similar to that found by McHugh and Shaw [Ref. 1] and illustrated in Figure 6. Interestingly, the collective input to null vibration for multi-input is less than that for single input. The wind tunnel tests culminated in the use of an adaptive automatic control system which employed Kalman filter estimation of parameters and optimal control theory. [Ref. 23,24]

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Wind tunnel testing prior to this point involved trial and error testing to calculate the optimal input for reduction of vibration. This worked well for single-input single-output, but the number of combinations possible for a multi-input multi-output made this approach unreasonable. For use on a production helicopter, an automatic system must be used. A closed loop active control system is the solution A block diagram of the control system used by Hammond [Ref. 23] is shown in Figure 9. The vibratory responses from the wind tunnel model are input to the electrical control unit (ECU) The ECU performs two functions. The first is the extraction of amplitude and phase of the 4p contribution from the total vibratory response signals. This is then passed on to the digital computer, which computes the optimal inputs. The digital computer then returns the sine and cosine components of the inputs to the ECU. The second function of the ECU is to take the inputs from the digital computer and convert them to 4p oscillatory analog signals having the correct amplitude and phase to drive the control servos. The 1p and 64p signals are used as part of the ECU in extracting the 4P component responses.[Ref. 23,24]
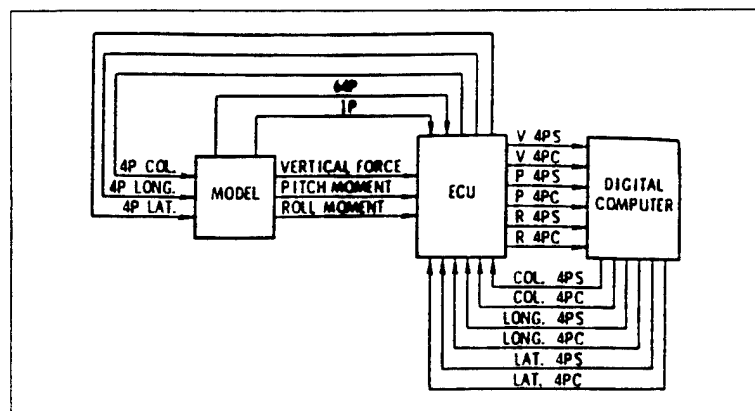
Figure 9. Block diagram of a closed loop higher harmonic control system [Ref.23]

The control algorithm to be used by the computer was the subject of much testing.

Four algorithms were tested, all were based on describing the system with the equation,

$$Z = Z_o + T * \Theta \qquad\qquad \text{(1 repeated)}$$

This equation represents the model as a static linear system. As such, a solution can be found which will null the 4P responses. The first part of the control strategy is to determine an initial transfer matrix. The values of Zo and T are determined through the use of a Kalman filter. Hammond describes a Kalman filter as,

"...a generalized form of the least-squares algorithm which accounts for the fact that the measured responses may be contaminated by noise and the transfer matrix may be changing with time." [Ref. 23]

With an initial value for Zo and T known any of the four controllers developed could be used. All of the controllers were based on a performance index, or cost function, which is minimized. The most successful of the four controllers tested assumed that the performance index was stochastic, and expressed the performance index as:

$$J = \{Z^T W_Z Z + \Theta^T W_\Theta \Theta\} \qquad\qquad \text{(3) [Ref. 23]}$$

In this equation, J is the function to be minimized, Z and Θ are the vectors previously described, and both W matrices are for weighting. Solving for a value of Θ which minimized J leads to the equation:

$$\Theta^* = -[\hat{T} W_Z \hat{T} + W_\Theta + C_1]^{-1}[\hat{T}^T W_Z \hat{Z}_o + C_2] \qquad\qquad \text{(4) [Ref. 23]}$$

Θ^* is the input required for minimization. The terms C_1 and C_2 introduce caution into the controller. The caution terms tended to make the controller much smoother in

minimizing the responses than other types. The resulting vibration reductions are shown in Figure 10. Note that the vibratory pitching and rolling moment reductions were much lower than those of vertical force. Although a considerable amount of testing was done to find the cause of this, no satisfactory explanation was found. The results presented in Figure 8 were obtained with the vertical response weighted more heavily than the moment responses, but different combinations were tested. Blade bending moments were found to increase for edgewise and torsion, but were reduced for flapwise. All loads were, however, well within the design load envelope. Hammond noted that the significant increases must be considered for the flight test program. [Ref. 23]
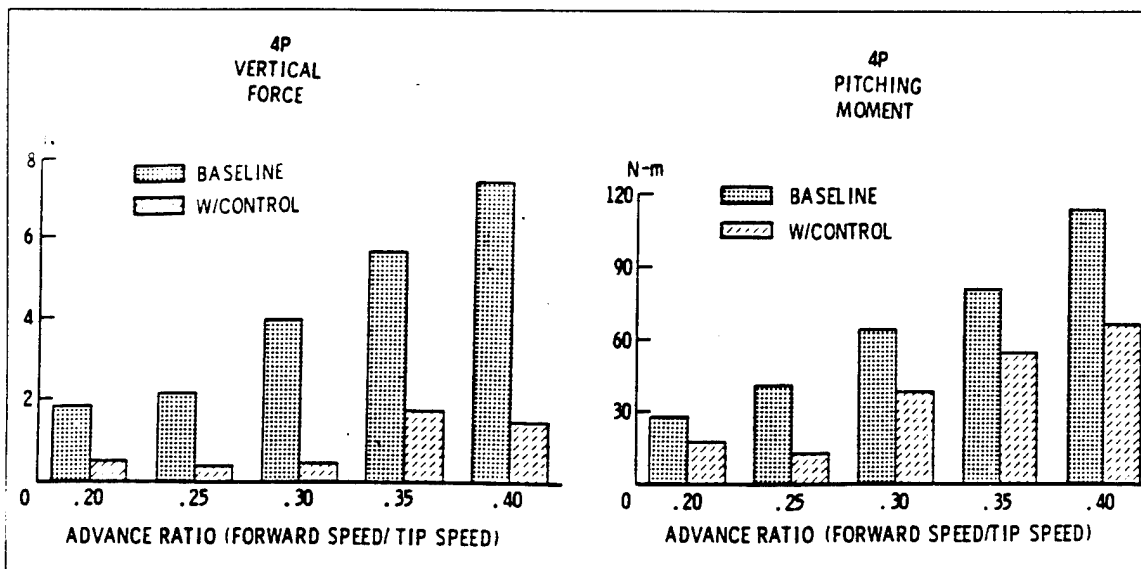
Figure 10. Variation of vibratory vertical force and pitching moment with advance Ratio. [Ref. 23]

The incorporation of a Higher Harmonic Control system into a flying helicopter requires several considerations for safety of flight and operations. These considerations
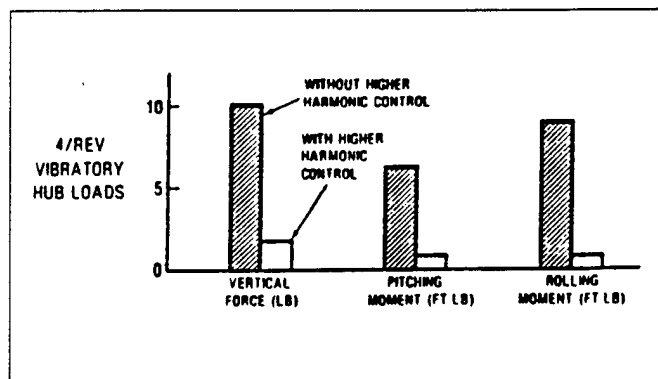
for mounting a Higher Harmonic Control system on an OA-6A helicopter were outlined

by Wood and Powers [Ref. 25]. Typically the OH-6A has no hydraulic boost system.

The actual aircraft used for flight testing was a special version with a hydraulic boost

system for the main controls. These modifications were made for some earlier tests

conducted, that do not pertain to the HHC tests. The typical systems needed to modify a

helicopter are load sensor or accelerometers, a microcomputer, a signal conditioner, and a

blade feathering actuation system. These elements, along with other modifications to the

OH-6A, are shown in Figure 11. Special considerations for flight worthiness include loss

of electrical or hydraulic power, loss of solution update, actuator hard-over, under-speed,

over-speed or over-stroke, out of phase actuator, engine failure or autorotation, one

actuator out operation. [Ref. 25]
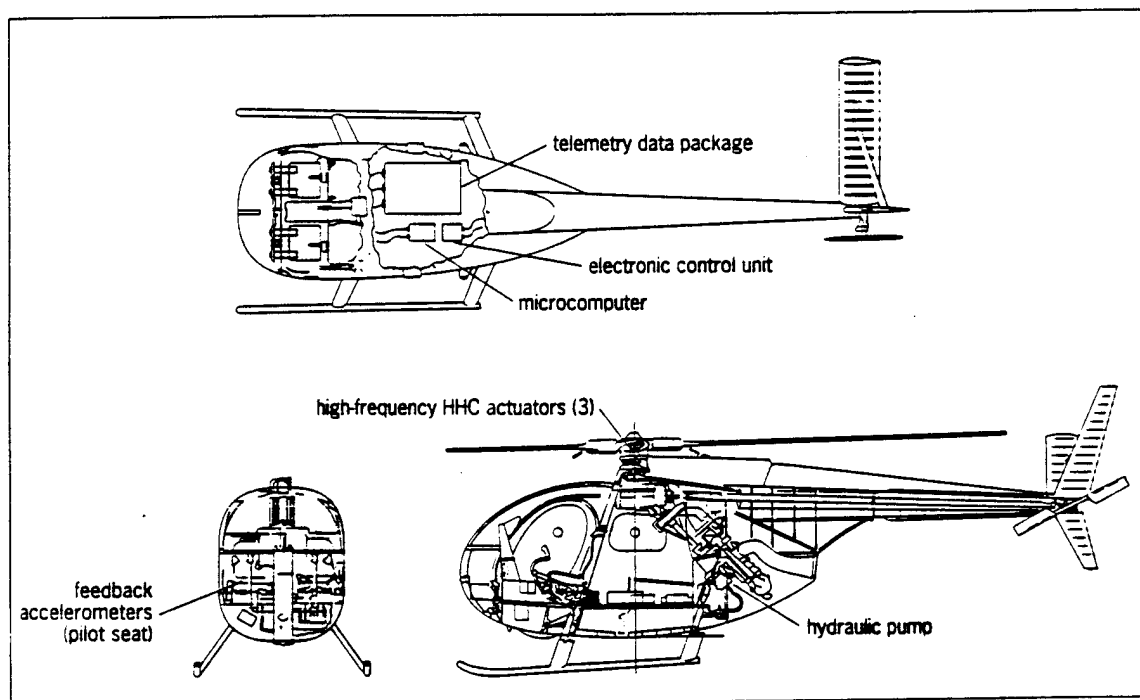
Figure 11. OH-6A Installation of Higher Harmonic Control. [Ref. 25]

One of the initial design decisions was to limit the system to one objective, minimization of 4P forces transmitted to the fuselage. Other major design decisions outlined by Wood, et al [Ref. 25] were the limiting of HHC weight to less than 1 percent of design gross weight, the use of hydraulic actuators in the fixed system downstream of the primary servos, use of the control algorithm outlined above, by Hammond [Ref. 23], replacing the Fast Fourier Transform with electronic analog techniques, and limiting sampling to two rotor revolutions.

While Hughes Helicopters continued HHC development towards a flying prototype, Boeing continued to advance their wind tunnel experiments. These were outlined by Shaw and Albion [Ref. 26] The Boeing work continued on the 10 foot rotor, now with a closed loop controller system. The system worked essentially the same as that described by Hammond [Ref. 23] and Wood et al [Ref. 25] with a few differences in the controlling scheme. The results of the wind tunnel experiments were essentially similar to those found by Hammond [Ref. 25], but with slightly greater reduction in overall vibratory hub loads, see Figure 12. While building the Boeing wind tunnel model used for the tests, one of the special considerations was the need to build actuators with much higher frequency response than ordinary hydraulic actuators. As would be expected, the 1/5th scale model required the use of much higher operating frequencies. [Ref. 26]

4/REV
VIBRATORY
HUB LOADS

WITHOUT HIGHER
HARMONIC CONTROL

WITH HIGHER
HARMONIC
CONTROL

10

5

0

VERTICAL
FORCE (LB)

PITCHING
MOMENT (FT LB)

ROLLING
MOMENT (FT LB)

Figure 12. Simultaneous Suppression of three Hub Load Components Achieved by a Closed-Loop HHC System in the Wind Tunnel. [Ref. 26]

A comprehensive and exhaustive study of Higher Harmonic Control, was published in 1980 by Shaw [Ref. 3]. This paper is an analytical study of the feasibility of a Higher Harmonic Control system. In particular it looks at using blade root pitch to control vibrations, applying pitch control outboard of the root, the impact of the two methods on blade aeroelastic characteristics, and applying the control system to adjust pitch input. Shaw's work is an excellent source of information for anyone interested in studying Higher Harmonic Control.

In 1981 Ham and Quackenbush [Ref. 27] tested an Individual Blade Control system (IBC) to suppress stall flutter. During forward flight, high angles of attack and their rapid variations on the retreating blade may cause torsional oscillations. These oscillations occur under certain combinations of torsional natural frequency, blade loading, and advance ratio. These torsional oscillations feed energy into the blade torsional mode. This torsional motion is damped out as the blade rotates toward the advancing side.

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Before the oscillations are damped out, they can put extreme loads on the control system. The system tested used IBC to suppress this problem. [Ref. 27]

Ham and Quackenbush used a one bladed, 21.2 inch span, rotor with an actuator in the rotating system for the tests. The one blade was balanced by two "dummy blades" consisting of threaded rod with adjustable counterweights. The system used accelerometers mounted on the blade for feedback to a linear controller. The tests were successful and four conclusions were made. First, stall flutter may be treated as a time varying aerodynamic phenomenon. Second, a simple linear model may be used to model the system. Third, rate feedback from the accelerometers to the blade pitch control motor can substantially increase the torsional oscillations. Fourth, the IBC concept should work as well for a larger scale system. [Ref. 27]

An overview discussing various control systems for HHC was presented by Chopra and McCloud [Ref. 28] in 1981. As described earlier, HHC controllers model helicopters in the frequency domain though a transfer function relating input harmonics to output harmonics. Vibration and stresses are reduced through minimization of a cost function. This type of control system is represented mathematically in equations 1 through 4. Controllers may be described as open-loop or closed-loop, using either on-line, off-line or adaptive identification of the model characteristics (Zo and T matrix). Chopra and McCloud analyzed the performance of these various types of controllers and their relative merits and problems. All of the controllers studied can be used effectively for a HHC system. Choice of a control system for HHC must be based on the capabilities of

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the system used, and the desired results. A detailed review of the different control systems presented by Chopra and McCloud is beyond the scope of this survey, and the interested reader is directed to reference 28.

Results of the long awaited first flight tests of Higher Harmonic Control were published by Wood et al [Ref. 2] in 1985. The paper summarizes the results of the flight tests conducted with the OH-6A from 1982-84. Flight tests were conducted throughout the helicopter envelope from hover to 100 knots, coordinated and windup turns, approaches and flares, and accelerations and decelerations. These tests were conducted both open loop and closed loop. [Ref. 2]

The OH-6A was equipped as described by Wood et al [Ref. 25] and used the closed loop adaptive control system described earlier by Hammond [Ref. 23]. The algorithm used by the HHC control system was the "cautious controller," details of which are presented by Molusis, et al [Ref. 29], and discussed by Hammond [Ref. 23]. The algorithm makes the assumption of a linear response. It is based on the matrix equations discussed previously. [Ref. 2]

For the flight tests, it was decided to locate the actuators between the mixer and stationary swashplate of the OH-6A helicopter. This configuration is shown in Figure 13. The electro-hydraulic actuators are of particular interest due to their high frequency response. The OH-6A rotor turns at about 480 RPM or 8 Hz. This places the 4P vibrations at 32 Hz, which is at a frequency considerably higher than can be obtained with a normal electro-hydraulic actuator (typically < 6 Hz). Special actuators specifically for

this program had to be built. The actuator stroke for a maximum of 1 degree pitch angle is +- 0.2 inches. This small stroke makes freeplay in the control system of considerable importance. A comprehensive program was conducted to minimize lost motion and local flexibilities in the primary mechanical controls. This resulted in an 80 percent reduction in freeplay as compared with the standard mechanical controls. [Ref. 2]
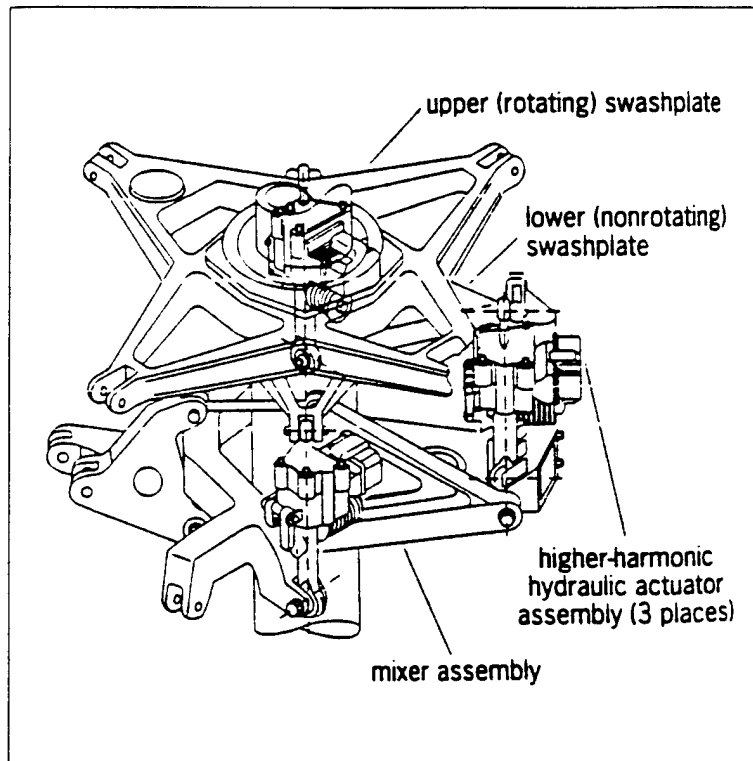
Figure 13. Swashplate Link Actuator Installation in the OH-6A.[Ref. 2]

The open loop test were very successful, confirming earlier analysis and wind tunnel tests. Initial closed loop tests (improved upon later) were also successful. The closed loop algorithm was designed to minimize vertical, lateral and longitudinal fourth harmonic vibrations at the pilot's seat. Typical results are presented in Figure 14. The

reduced effectiveness of HHC at higher airspeeds can be seen. Blade loadings were found
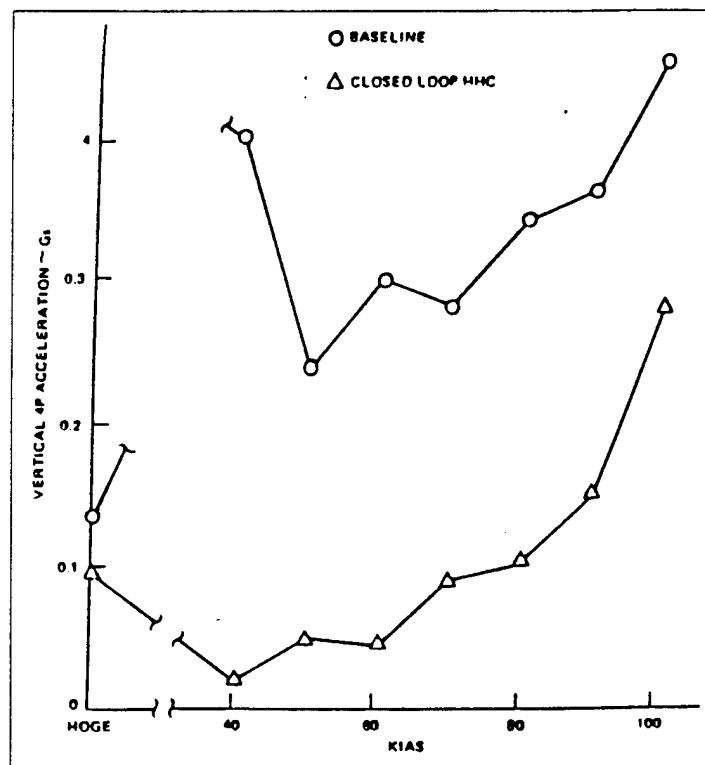
to be close to those expected.

Figure 14. Closed Loop HHC-4P Vertical Pilot Seat Accelerations versus airspeed.[Ref. 2]

A significant finding was a reduction of required power when the HHC system

was engaged. This is shown in Figure 15. No explanation of this behavior was available.

It was suggested that this be the subject of some future investigation. Flight tests

continued until May of 83, then the HHC system was refurbished and changes were made

to the algorithm. Calculation time was reduced, changing total update time from 257 ms

to 163 ms. Additionally the method for calculation of the Kalman gain vector was

changed. These modifications resulted in improved controller performance, as illustrated

in Figure 16.[Ref. 2]

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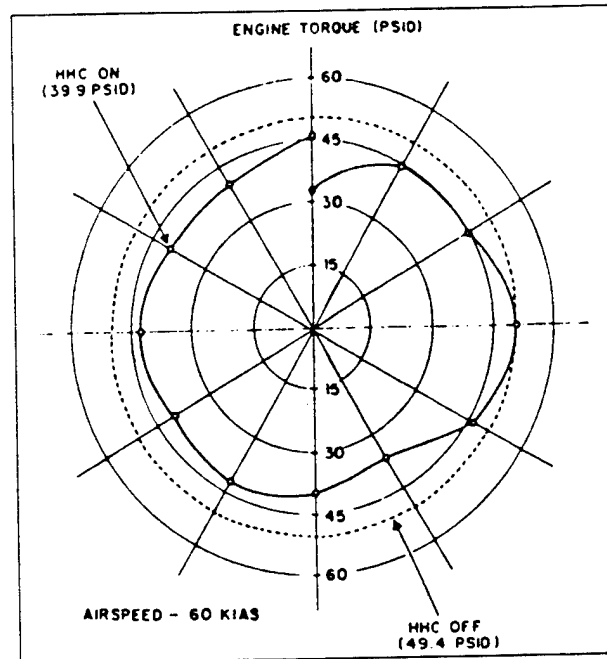
Figure 15. Effect of HHC on engine torque pressure at 60 KIAS for lateral input of ± 0.33 degrees.[Ref. 30]
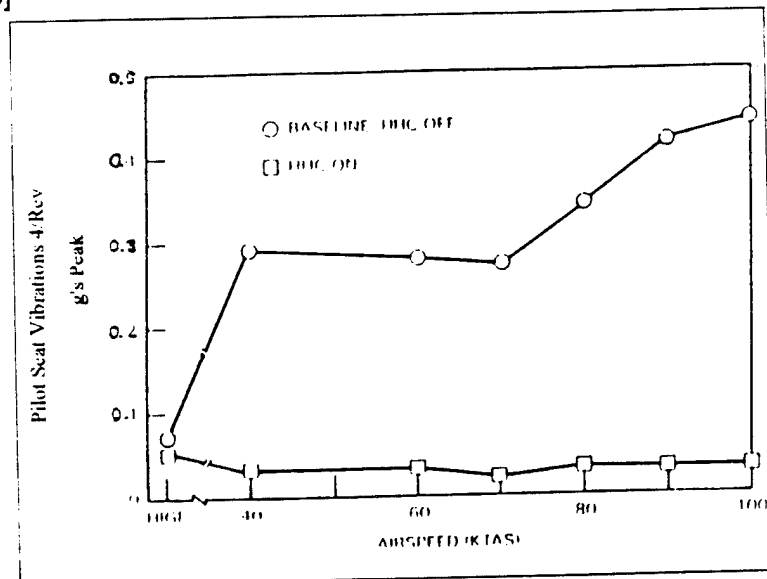
Figure 16. Closed Loop HHC 4p vertical pilot seat accelerations versus airspeed. [Ref. 2]

Flight crew members reported that the helicopter would begin to climb once HHC

had been turned on. If level flight was maintained, it was noted that the reduction in

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power revealed by a reduction in main rotor shaft torque was accompanied by a corresponding reduction in engine torque pressure. [Ref. 30]

In 1986, Polychroniadis [Ref. 31] presented the results of a research program to test Higher Harmonic Control by Aerospatiale Helicopters.. The Aerospatiale tests began by building on earlier work and culminated in a flight test program on the SA-349 three bladed experimental aircraft, derived from the SA 342 Gazelle. The flight tests were conducted in 1985 and finished with the testing of a closed loop HHC system throughout the flight envelope. The two primary areas for study were activation through the non-rotating swashplate and selection of a self adaptive control system. Actuation through the non-rotating system gave several advantages in simplification over an IBC system, and so was chosen.

Three types of algorithms were tested for the optimum control computations; a) Deterministic Adaptive Algorithm (AAD) b) Stochastic Adaptive Regulator (RAS) c) Stochastic Adaptive Regulator with Evaluation of Vibrations (RASEV). Like previous algorithms, they were all based on the same linear relation of Equation 1. The algorithms determined optimum control by minimizing a cost function. [Ref. 31]

The ADD was initialized by input control variations to generate the T matrix, whereas the RAS and RASEV identify the T matrix through Kalman filter methods. The RASEV also identifies the vector Zo without HHC filtering. Analytical simulations were performed to test the operations of the algorithms and the gains brought in by the system.

Figure 17 shows the expected effects of the algorithms predicted by the analysis. Note the difference in vibration levels depending upon choice of control algorithm. [Ref. 31]
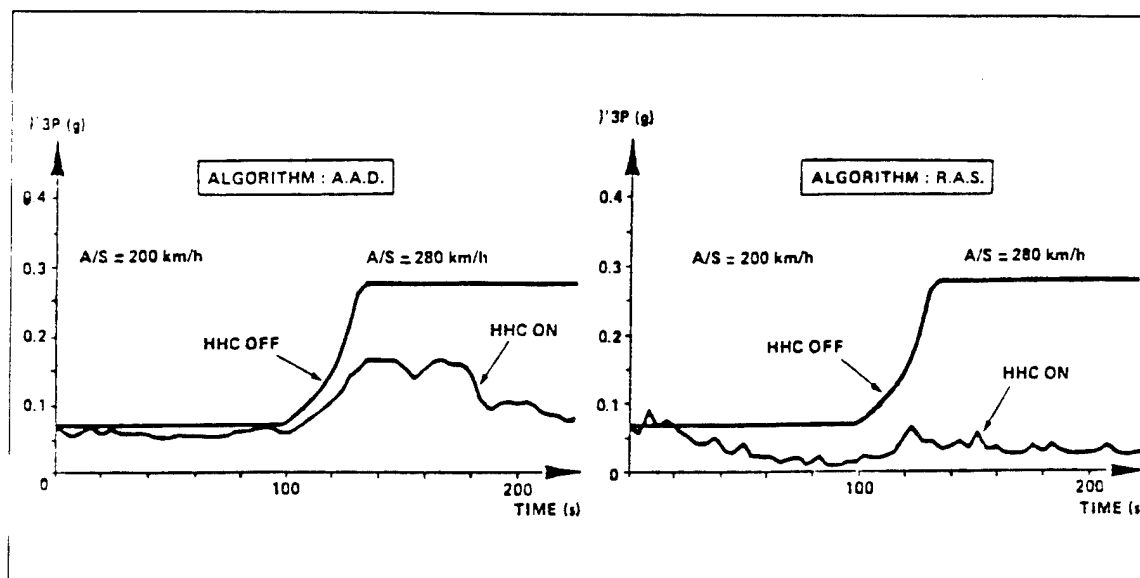

Figure 17. Analytical simulation (level flight acceleration) [Ref. 31]

After the validity of the algorithms was substantiated analytically, the HHC system was tested on a rotor test stand. These tests confirmed operation of the HHC system, and flight tests were begun. The SA 349 is equipped with a bi-directional focusing system. This is a passive suspension system. Flight tests were conducted for two aircraft configurations. One with the passive suspension system, operating, and one with the system disabled. The later corresponds to the most likely configuration for HHC use. Only the results with the passive suspension system off were presented by Polychroniadis. [Ref. 31]

The system worked well and results were close to those predicted. The RASEV algorithm proved to work the best in all flight regimes. The HHC system was limited to $\pm 1^{o}$ travel to limit large pitch link loads encountered during initial tests. Vibration level

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was shown to be related to control travel, and extrapolation deduced that vibration could

be further reduced at higher airspeeds if HHC used larger pitch angles. The general

results for overall vibration reduction are shown in Figure 18. Cabin vibration was

reduced 80% at 250 km/h (135 knots). Considering the fact that the OH-6A was flown to

100 knots (HHC angle <1 degree) and the sikorsky S-76 to 150 knots (HHC angle <2

degrees) this is consistant with other flight programs. [Ref.31]
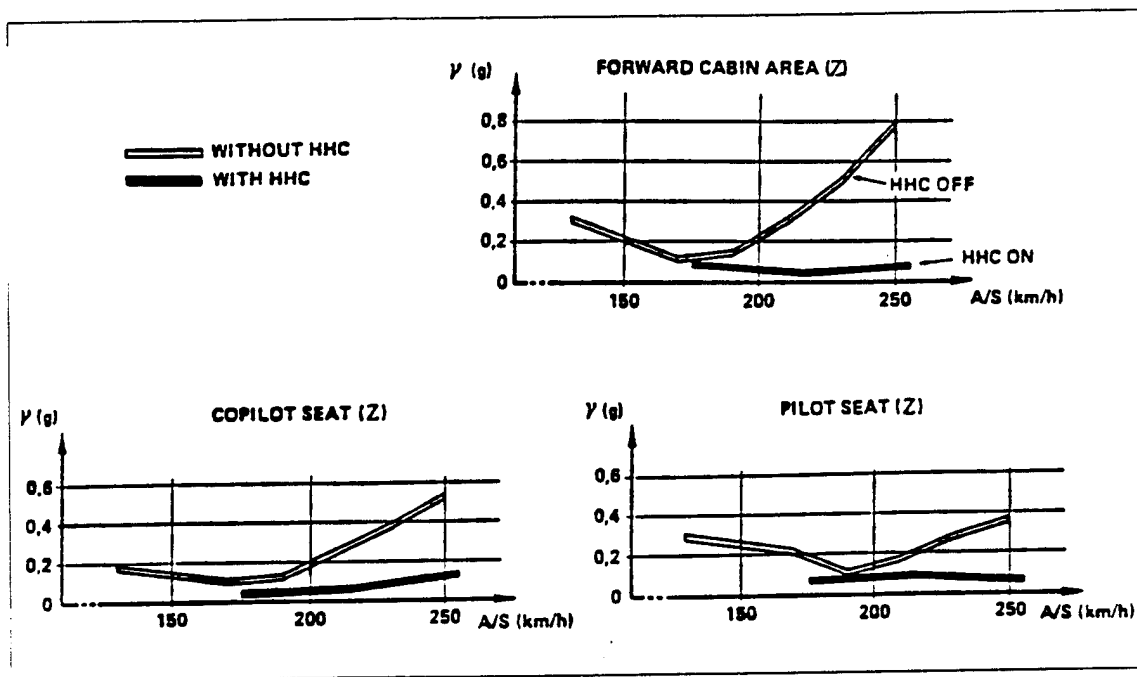
Figure 18. Effectiveness of Higher Harmonic Control system in level flight on the SA 349.

[Ref. 31]

While the Hughes OH-6A program was conducting their flight testing, Sikorsky

Aircraft Division of United Technologies was developing an HHC system for the S-76A.

The results of the flight testing were presented in papers by Miao, et al [Ref. 32], and

Walsh [Ref. 33] The S-76 flight tests were successful in reducing vibrations from hover to

41

150 kts. Vibration reduction was also achieved for varying rotor speed and during
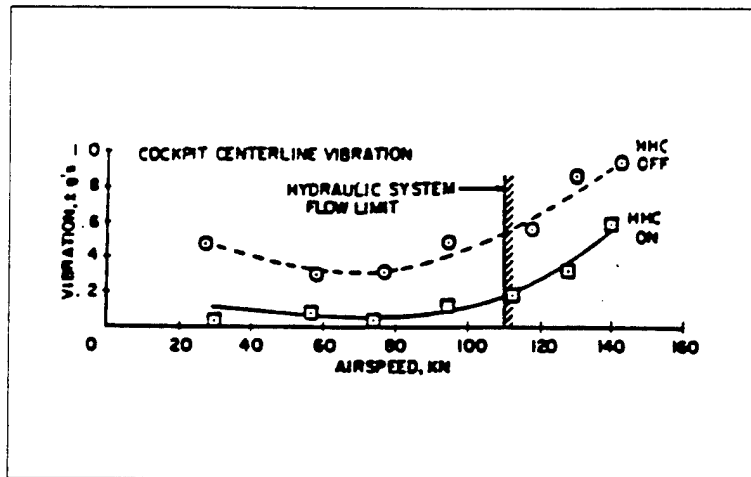
maneuvers. Some results are shown in Figure 19.

Figure 19. Reduction in cockpit centerline vertical vibration for the S-76 [Ref. 32]

The S-76 was modified similar to the OH-6A. One noticeable difference was the

placement of the HHC actuators upstream of the primary servos, that is between the

primaries and the cockpit controls. Although the flight tests were successful, desired

vibration reduction was not achieved in all flight conditions. Several shortcomings in the

design of the S-76 HHC system contributed to the less than desired results. At higher

speeds, the required amplitude inputs of the HHC system were too large for the installed

hydraulic system to fully supply the HHC actuators. The location of the HHC actuators

upstream of the primary servos resulted in a long control path to the rotor head. The

control path contains many linkages, and the primary servos. Each linkage and bearing in

the control path can absorb some of the HHC actuator input. This causes the HHC

control system to demand greater actuator movements to affect the desired change in

rotor blade angle of attack. Control path length and losses were also a concern during the

development of the HHC system on the OH-6A. To avoid this, the design for the OH-6A HHC system replaced several alloy components with stronger ones, used close tolerance rod end bearings, and placed HHC actuators as close as possible to the swashplate [Ref. 24]. The primary servos used for the S-76 flight tests were modified for higher than normal frequency response. Inadequate hydraulic supply also had a negative affect on the primary servos. The HHC actuator position also allowed the HHC input to feed back to the cockpits controls. Together, the long control path, and the upstream travel of the HHC inputs overtaxed the capabilities of the hydraulic system. As a result, the HHC amplitude input was limited at higher speeds. Crosstalk through the control mixer was also a problem. The S-76 flight control system mixes pilot inputs (cyclic, collective and yaw) to reduce the effects of coupling, i.e. the mixer reduces the required rudder and cyclic input required for a change in collective setting. Feedback through the mixer allowed uncommanded motion of off-axis main rotor servos. [Ref. 32,33]

Maio [Ref. 32] also presented a correlation study comparing analytical results to flight test data to validate the analysis for future use. The analytical predictions showed reasonable correlation for some of the operating conditions, however accurate prediction of HHC amplitude requirements at high speed was a concern.

The results of wind tunnel testing of a dynamically scaled three bladed CH-47D Chinook rotor were presented by Shaw, et al [Ref. 34] in 1985. The HHC system used for the tests was able to simultaneously and completely suppress vertical and in-plane 3p

hub forces continuously as the model was "flown" throughout its test envelope up to 188 knots.

During the wind tunnel tests, three control systems were evaluated. The most successful featured fixed gain feedback control. This is a significantly different system from the adaptive controller used in the flight tests of the OH-6A, the S-76, and the SA 349. Testing showed the fixed gain controller to be faster and simpler than the adaptive gain systems. The fixed gain controller did not change and update the T matrix while in operation, but selected it from a library of existing matrices that were previously determined from wind tunnel testing. Another difference in these tests was the placement of the sensors for feedback to the controller in the rotating system. These sensors measured hub loads rather than vibrations in the airframe. [Ref. 34]

Also significant was the demonstration of hydraulic seals which showed little wear after 15 million high frequency cycles. This is important, as seal life on a production HHC system has been a serious consideration. [Ref. 34]

Results of wind tunnel tests conducted on a scale BO-105 rotor at DNW by DFVLR were published by Lehmann [Ref. 35] in 1985.[2] The BO-105 rotor is a four bladed hingeless system. The tests were designed to prove the specifically designed hardware and software under realistic conditions for the scale BO-105 rotor. The scale of the model was not given. Similar to previously wind tunnel tests, Lehmann systematically measured a cost function of 3P, 4P and 5P inputs to the rotor. For these tests, the cost

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[2] DNR is the German national wind tunnel, and DFVLR is the German equivalent of NASA.

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function consisted of the three forces, x, y, and z on the rotor as moments about the x and y axis. After testing separate inputs of 3P, 4P and 5P, simultaneous inputs of all 3 were tested. The tests concluded with expected results. Some significant findings are as follows. First, a 90 percent reduction in the cost function (vibration levels and moments combined) was achieved. Second, the chosen cost function was proven to be valid for feedback to the controller. Third, acceleration forces on the mechanical control hardware (actuators and linkages) were found to affect the measurements of the dynamic loads. Fourth, pitch link loads were nearly independent of input frequency, but proportional to pitch amplitudes. Fifth, variation in trim states were observed, but these variations did not reduce HHC effectiveness. Sixth, relatively large input angles were required in low speed flight. The report concludes further testing to expand the HHC envelope is still required. [Ref. 35]

A preliminary design investigation for implementing a HHC system on a UH-60A was published by Shaw, et al [Ref. 36] in 1987. The report is quite detailed and predicts some favorable results for installing HHC on the already operational UH-60A. Two major benefits are predicted in the report. First, a reduction in average fuselage vibration levels from 0.11 to 0.07 g, resulting in improvements of 12 percent for overall aircraft reliability and 7 percent reduction in maintenance requirements (MMH/FH) will give an estimated savings of $680,000 per aircraft over 20 years. This will more than offset the RDT&E and investment cost for of HHC of $260,000 per aircraft for a fleet of 100. Second, an HHC system would reduce the weight of the vibration system by 146 lbs, or 0.9 percent

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by removal of the current system of bifilar and tuned vibration absorbers. When the actuation power and the reduction in weight is considered, payload is increased by 96 pounds for a 2 hour mission. [Ref. 36]

The investigation analyzed several different configurations for actuation, vibration sensing and controllers and made the following conclusions.

- The HHC actuators should be integral to the flight control actuators.

- The HHC system should be fail-safe rather than fail-operational.

- HHC actuator control electronics should be dual to prevent excessive failure transients of the high-rate actuators.

- Blade modifications will probably required to detune the second chorwise mode from 5P to maintain blade life.

- Upper control linkage bearings will have to be redesigned to eliminate freeplay. Other portions of the control system do not require stiffening.

- Principle risks of installing a HHC system are due to unexplored characteristics of HHC in maneuvers with rotor stall.

- Power requirements of the rotor due to HHC are uncertain, and may either increase or decrease, but are likely than 2 percent either way.

Since the flight tests of the 1980's, research activity in the field of HHC has been primarily analytical. Some representative papers in this area include two by Robinson and Friedmann [Ref. 37, 38]. A summary of some of the results of these two papers along with some additional ideas were published by Freidmann [Ref. 39]. These analytical

studies featured an improved mathematical model or the rotor that includes the effects of geometric nonlinearities, high frequency unsteady aerodynamics and a new trim procedure based on a full flap-lag tortional model. Principle findings of these studies are listed below:

- Comparison of baseline to optimal reductions in vibration showed principle differences were in the torsional and blade flap response. Overall response magnitudes changed little, but large 4P components were introduce to cancel the vibrations

- Comparison of HHC response on roughly equivalent articulated and hingeless rotors showed equivalent reductions in shears produced large increases in moments of the hingeless rotor, and only moderate shear increases in the articulated rotor. Additionally, much larger HHC angles were required for the hingeless system compared to the articulated rotor to achieve the same reductions in hub shears.

- Attempts to reduce both hub shears and moments were not very successful for either the hingeless or the articulated rotor. For the hingeless rotor, large moments decreased greatly at the expense of poor shear reduction. This indicates that HHC may be more difficult to implement on a hingeless rotor.

- Power requirements of a HHC system were found to increase 1.44 percent for the hingeless rotor and a 0.18 percent for the articulated rotor.

- Aeroelastic stability margins of the blade in forward flight were found not to degrade significantly. [Ref. 39]

Recently a study was made for the U.S. Navy on the implementation of HHC on the Navy version of the Backhawk, the SH-60B Seahawk. This report by Fenn, et al [Ref. 40], builds on the previous study by Shaw, et al [Ref. 36]. The study by Fenn, et al [Ref. 40] briefly reviews available information on HHC, and then selects options in actuation and control to arrive at a baseline/conctept HHC design for implementation in the SH-60B.

Fenn, et al, [Ref. 40] point out equipment costs and crew safety concerns require a well documented demonstration program. Real stresses must be determined to verify and prove structural integrity and address fatigue life expectancy. Additionally, the system must be proven fail-safe before flight qualification. To this end, the study is aimed at establishing design specifications and requirements for an HHC ground testbed. This testbed will be used to demonstrate a single degree of freedom HHC on an SH-60B control system as well as produce quantitative information in the areas of stress, safety, and fatigue life.

McDonnell Douglas Corp. has begun testing a rotor system with two flaps on the trailing edge of the rotor blade in addition to conventional blade root actuation. The system is similar to the Kaman Controllable Twist Rotor discussed previously (illustrated in Figure 5), and uses a dual actuation system analyzed by Shaw [Ref. 3]. The second flap in this proposed system is for improved rotor tracking. Actuation for the flaps may be piezoelectric, magnetostrictive, or shape-memory alloy devices. With this HHC system, McDonnell Douglas Corp. hopes to achieve a ride comparable to that of a fixed wing jet

and 50 percent quieter than a comparable helicopter.   It is hoped that a full working

aircraft with this system will be flying in 1998. [Ref. 41]

III. PLANS FOR NEARTERM NPS TESTS

A. BACKGROUND

Since the Navy has demonstrated interest in installing an HHC system on an SH-60B Seahawk [Ref. 40], and the staff at the Naval Postgraduate School has been active in HHC research [Ref. 2,30], it is only natural that the Naval Postgraduate School plans to participate in future testing. To this end, studies have been made into HHC by students, and plans are currently being made for testing of an OH-6A rotor on the U.S. Naval Academy whirltower.

Following is a brief review of NPS studies in the area of HHC, and some initial considerations for the Whirltower tests.

B. BRIEF REVIEW OF NPS HHC STUDIES

The first study of HHC at NPS was conducted by Sarigul-Klijn [Ref. 42]. In this study Chaos methods were used to analyze data from the OH-6A flight tests of Wood, et al [Ref. 3]. Analysis shows the presence of chaos in the mostly periodic helicopter vibrations. This Chaos was shown to limit the ability of HHC to reduce vibrations. Sarigul-Klijn introduced a new technique based on chaos theory that results in rapid determination of the limits of HHC vibration reduction, rapid determination of the best phase for a HHC controller, determines minimum controller requirements, and shows the controller transfer matrix to be linear and repeatable when vibrations are defined in a "Rotor Time Domain" while also nonlinear and unrepeatable in the "Clock Time Domain".

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Preliminary considerations for implementing HHC on an SH-60B were presented by Webb [Ref. 43] in 1990. This study predates the report conducted for the Navy by Fenn, et al [Ref. 40]. The thesis covers many of the same areas in less detail. Conclusions by Webb are the same as that reached by Shaw, et al [Ref. 36].

Motivated by the reduced power requirements found by Wood, et al [Ref. 2] in the OH-6A flight testing, investigations were made into the area of unsteady aerodynamics to explain this behavior . These investigations include NPS theses by Abourahma [Ref. 44] and Couch [Ref. 45] and another study that combines adds to these two by Wood, et al [Ref. 30]. In this investigation, unsteady aerodynamics of HHC with wake effects were studied to see if the power were feasible. Both classical closed-form methods and numerical panel codes were used. Because the main interest was in performance, the primary emphasis was on the effect of unsteady aerodynamics on the drag of the blade. It is known that an airfoil oscillating in plunge can achieve propulsion effects, known as "Katzmayr" effect. Wood et al [Ref. 30], showed that this propulsive force can be doubled in the presence of shed wake vorticity of the proper phase, and depending on wake spacing, reduced frequency, and phase, may even provide a propulsive force acting on the blade. The paper concludes that a) the reduced torque found in several flights of the OA-6A [Ref. 1] were feasible, b) the performance benefits changed with airspeed due to the wake being transported further from the rotor at higher speed, c) the relatively poor closure or repeatability of some of the flight tests may be due to the sensitivity of the

OH-6A to wake position, and the difficulty in repeating wake position during flight testing.

C. PLANNED WHIRL TOWER TESTS

The favorable results found in the NPS investigations suggest that performance improvements may be repeatable and predictable. Since the OH-6A tests were the only flight tests that showed such a substantial improvement in performance, more detailed analysis is desirable.

The NPS plans to mount an OH-6A rotor on a whirltower, then conduct open loop rotor performance testing a HHC system. The whirltower is located in the US Naval Academy, and illustrated in Figures 20 and 21. This whirl tower was originally designed for testing of circulation control rotors. To test a conventional rotor, several modifications are required.   The plans call for using the HHC system that was installed on the OH-6A as well as the rotor.
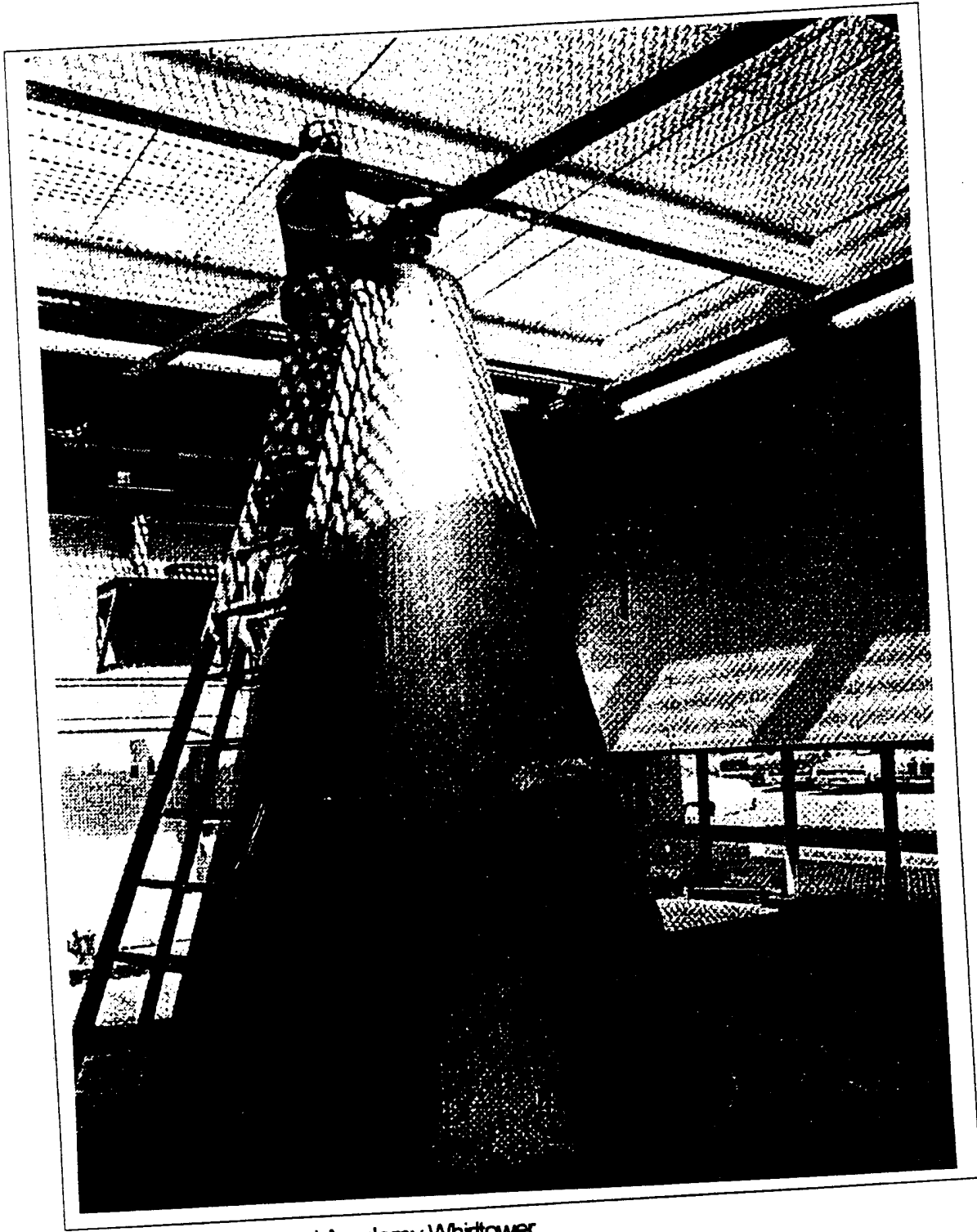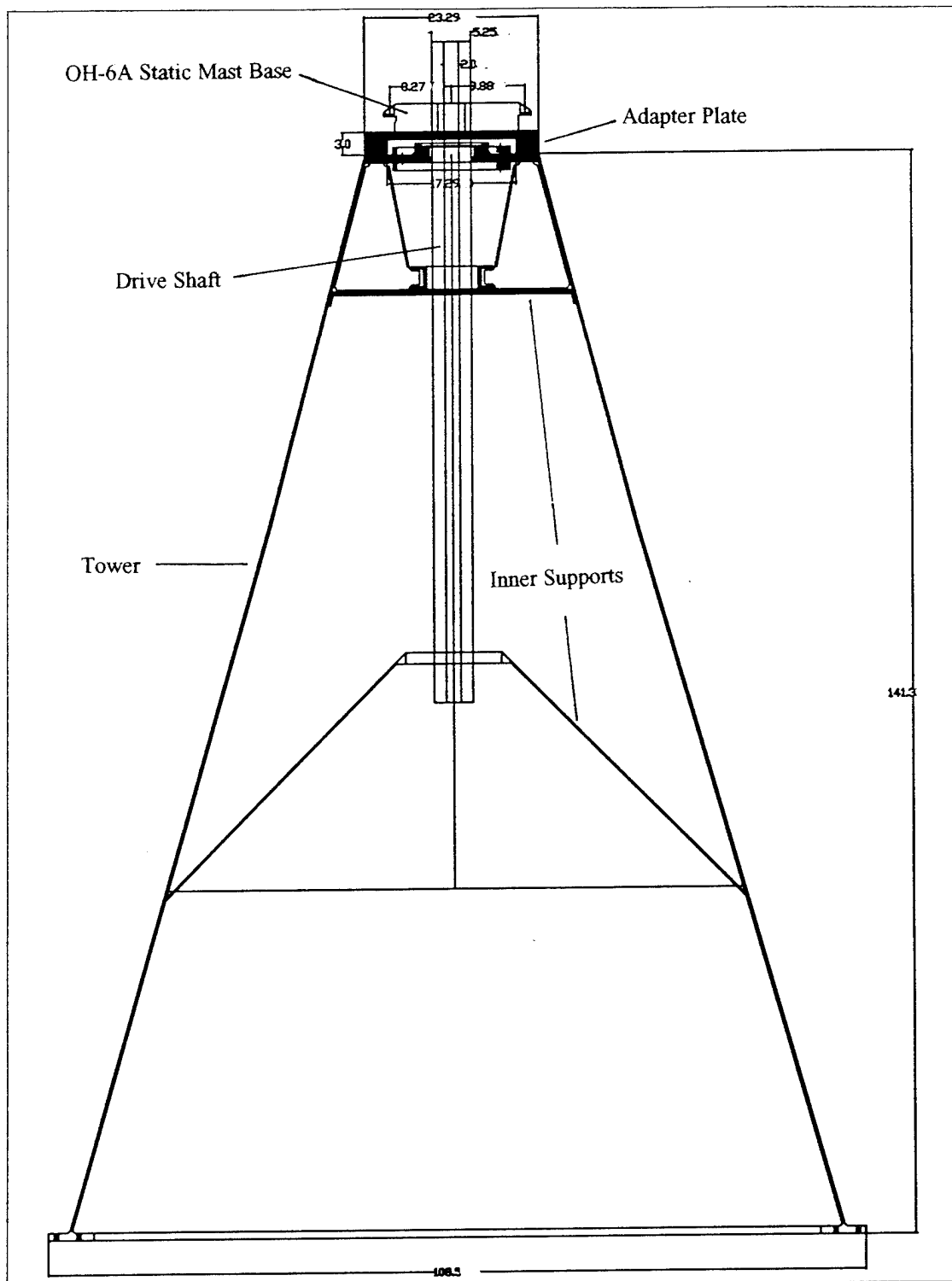
Figure 20. The US Naval Academy Whirltower

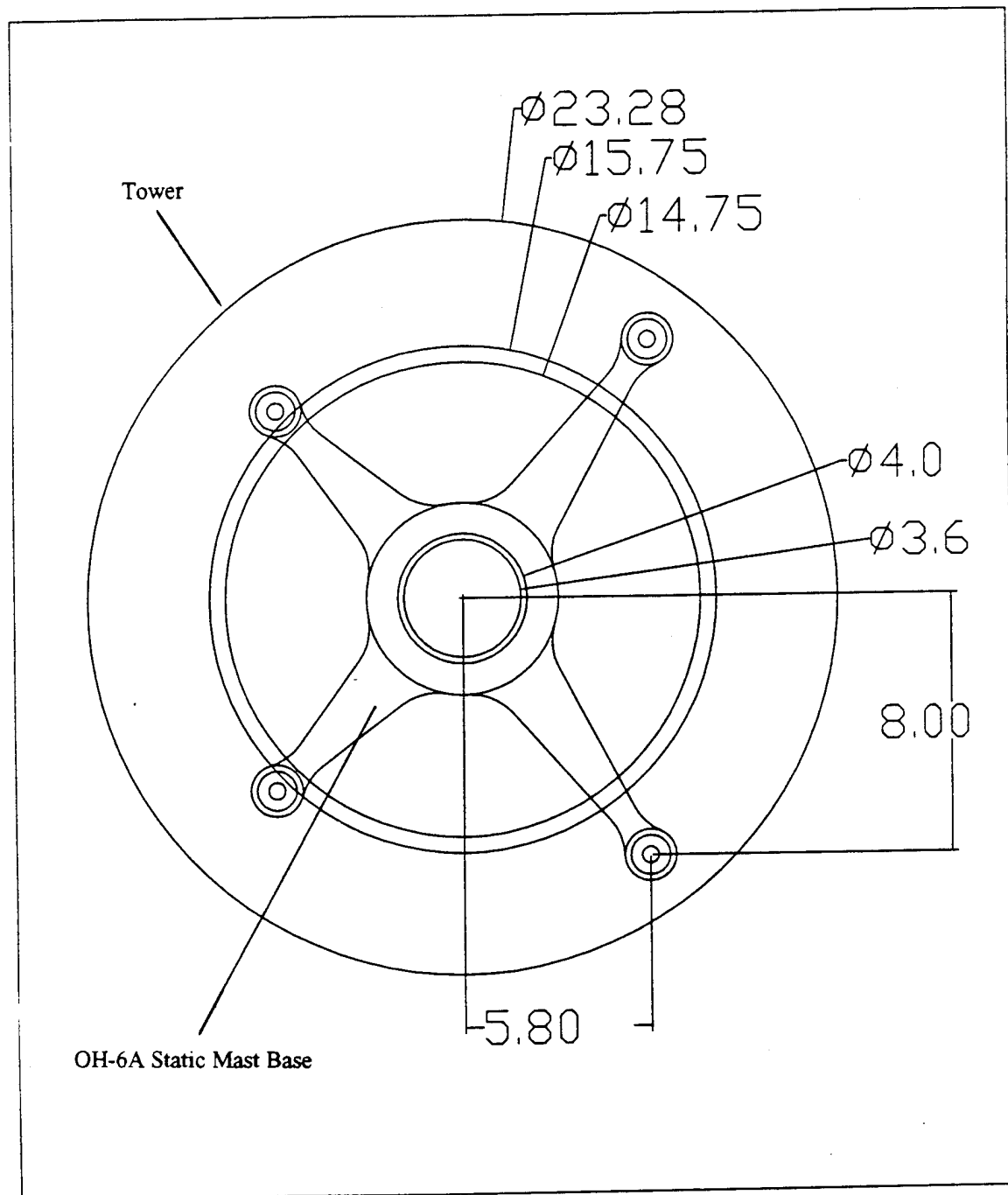**Figure 21.** Cutaway view of the Whirltower

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Several areas of requiring investigation before testing are as follows:

- The OH-6A rotor blades will have to be reduced by two feet to fit in the test area. This may cause undesirable effects on the placement of the blades natural frequencies. Since the rotor will not have to be flight worthy, addition of weight on blade nodes or anti-nodes will likely solve this problem.

- The motor currently in the whirl tower must be upgraded from its present 50 hp to a more suitable level for driving the rotor head. Plans call for 200 hp. Based on the size and construction of the whirltower, this may not pose any problem, however, it must be examined.

- The slipring assembly in the whirl tower is old and worn and may not give the fidelity required for the proposed tests. It is likely that it will have to be replaced, or another method for gathering data from the rotating system will have to be found.

- Actuators must be installed to replace the control inputs normally coming from the cockpit that control collective and cyclic settings.

- A hydraulic supply system for the HHC actuators and possibly the cyclic and control actuators will have to be added to the facility

- A means of attaching the drive shaft from the motor to the drive shaft of the rotor will have to be devised.

- An adapter for attaching the static mast of the OH-6A to the tower must be made. One possible adapter is proposed below.

The OH-6A rotor is mounted to a static mast. A static mast is a non-rotating tubular structure with four legs that transmits forces from the rotor down to the fuselage. The bearings for the rotation of the rotor are located at the top of the static mast, in the middle of the rotor disk. Torque to the static mast is transmitted from a drive shaft inside the static mast, up through the top to a flange, which in turn transmits torque to the rotating portion or the rotor. This system is ideal for mounting on the whirltower, as a transmission is not required. Two views of a proposed adapting plate are shown in Figures 22 and 23.
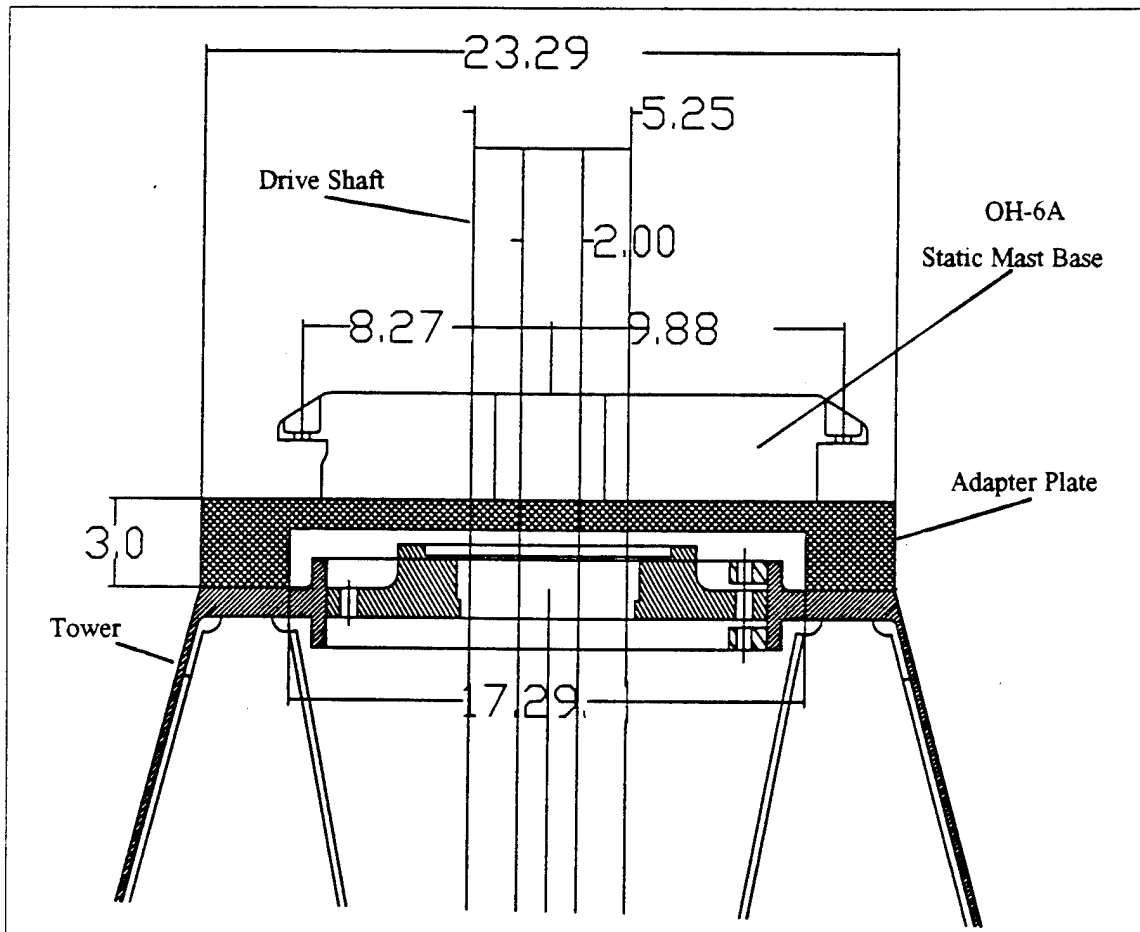
Figure 22. Side view of the proposed adapter plate.

Figure 23. Top view of the proposed adapter plate.

The adapter plate is essentially a circular aluminum plate three inches thick with a

hole in the center for clearance of the top bearing in the whirltower and a coupling

between the drive shafts of the rotor and the motor.

IV. CONCLUSIONS AND RECOMMENDATIONS

Higher Harmonic Control has been described. Important studies in its development have been summarized. The involvement of the NPS in the development of HHC has been shown. Considerations for nearterm testing have been presented.

Higher Harmonic Control is an effective system for reduction of helicopter vibration. A great deal of research has been conducted to show this. To this point an optimal HHC design has not been determined that can be used for continuous flight operations. Although research has been directed twords vibration reduction, accoustic reductions have also been found. It is recommended that anyone interested in improving helicopter aviation consider this proven, low risk, system.

APPENDIX

Brown, T.J., McCloud, J.L. III, "Multicyclic Control of a helicopter Rotor Considering the Influence of Vibration, Loads, and Control Montion," *AHS Proceedings*, 1980.

Davis, M.W., "Refinement and Evaluation of Helicopter Real-Time Self-Adaptive Active Vibration Controller Algorithms" NASA CR 3821 1983.

Hamm, N.D., "A Simple System for Helicopte Individual-Blade-Control Using Modal Decomposition", *Vertica*, 4, 1, 1980.

Hamm, N.D., and McKillip, R.M. jr., "A Simple System for Helicopter Individual-Blade-Control and Its Appication to gust Alleviation", *Proc. Sixth European Rotorcraft Forum*, Bristol, England, September, 1980.

Hamm, N.D., and Young, M.I., "Torsional Oscillation of Helicopter Blades Due to Stall", *Journal of Aircraft*, pp 218-224, May-June, 1966.

Hamm, N.D., "Helicopter Individual-Blade-Control Research at MIT 1977-1985", *Vertica 11*, 109-122, 1986

Hammond, C.E., "Helicopter Vibration Reduction Via Higher Harmonic Control", Structures Laboratory, U.S. Army Reasearch and Technologies Laboratories, Proceedings of the Rotorcraft Vibration Workshop, NASA Ames Reasearc Center, February 1978.

Hammond, C.E. and Weller, W.H., "Recent Experience in Testing of a Generalized Rotor Aeroelastic Model at Langley Research Center", *Proceedings of the Second European Rotorcraft and Powered-Lift Aircraft Forum*, September 1976.

Jacob, H.G., Lehmann, G. , "Optimization of Blade Pitch Angle for Vibration Reduction: a Wind Tunnel Demonstration:, *Vertica*, Vol. 7, No.3, 1983.

Kretz, M., "Reasearch in Multicyclic and Active Control of Rotory WIngs', *Vertica 1*, 95-105, 1976.

Lehmann, G., "A Digital System for Higher Harmonic Control of a Model Rotor", *Vertica*, Vol. 8, No. 2, 1984.

McCloud, J.L. III, "Multicyclic Control for Helicopters: Research in Progress at Ames Research Center," *AHS Proceedings*, 1980.

McCloud, J.L. III, "Multicyclic Control for Helicopters: Research in progress at NASA Ames Research Center", *AHS Proceedings*, 1980.

McHugh, F.J. and Shaw, J., "Benefits of Higher-Harmonic Blade Pitck"Vibration reduction, Blade-load reduction and Performance improvement". *Proceedings of the American Helicopter Society Mideast Region Symposium on Rotor Technology*, August 1976.

McHugh, F.J. and Shaw, J., "Helicopter Vibration Reduction with Higher Harmonic Blade Pitch". *Proceedings of the Third European Rotorcraft and Powered-Lift Aircraft Forum*, September 1978.

Molusis, J. A., "The Importance of Nonlinearity on the Higher Harmonic Control of Helicopter Vibration", AHS Proceedings, 1983.

Quackenbush, T.R., "Testing and Evaluation of a Stall-Flutter-Supprestion System for Helicopter Rotors Using Individual-Blade-Control", M.I.T. Aeroelastic and Structures Research Laboratory TR-196-3, August 1981.

Reichert, G., "Helicopter Vibration Control - A Survey", *6th European Rotorcraft Forum*, Bristol, Sept. 1980, Paper No. 10.

Shaw, J. Albion, N., " Active Control of Rotor Blade Pitch Control for Vibration Reduction: A Wind Tunnel Demonstration", *Vertica*, Vol. 4, No. 1, 1980.

Sissingh, G.J. and Donham, R.E., "Hingeless Rotor Theory and Experiment on Vibration Reduction by Periodic Variation of Conventional Controls", *Rotorcraft Dynamics*, NASA SP-352, February 1974.

Taylor, R.B., Farrar, F.A., "An Active Control System for Helicopter Vibration Reduction by Higher Harmonic Pitch," *AHS Proceedings*, 1980.

Taylor, R.B., Zwicke, P.E., Gold, P., Miao, W., "Analytical Disign and Evaluation of an Acitve Control System for Helicopter Vibraiton Reduction and Gust Alleviation", NASA CR 152377 1980.

Yen, J.G., "Vibration Reduction with Higher Harmonic Blade Feathering For Helicopters with Two-Bladed Teetering and Four-Bladed Hingeless Rotors," *AHS Proceedings*, 1980.

REFERENCES

1. McHugh, F.J., Shaw, J, "Helicopter Vibration Reduction with Higher Harmonic Blade Pitch", Journal of the AHS , Vol 23, Number 4, October 1978

2. Wood, E.R., Powers, R.W., Cline, J.H.,Hammond, C.E., "On Developing and Flight testing A Higher Harmonic Control System", *Journal of the AHS*, January, 1985.

3. Shaw, J.T., "Higher Harmonic Blade Pitch Control: A System for Helicopter Vibration Reduction.", Doctoral Dissertation, Massachusetts Institute of Technology, Boston Mass., 1980.

4. "Guide for the Evaluation of Human Expxposure to Whole-Body Vibrations", ISO 2631-1978(E), International Organization for Standardization, 1978.

5. Stewart, W. "Second Harmonic Control of the Helicopter Rotor". Aero Research Council, Reports & Memranda 2997, London, August 1952.

6. Arcidiacono, Peter J. "Theoretical Performance of Helicopters Having Second Higher Harmonic Feathering Control". Journal of the American Helicopter Society, April 1961.

7. Wernicke, R.K., and Drees, J.M., "Second Harmonic Control." *AHS Proceedings* 1963.

8. Bell Helicopter Company. "An Experimental Investigation of a Second Harmonic Feathering Device on the UH-1A Helicopter". U.S. Army Transportation Reasearch command, Fort Eustis, Virginia, TR62-109, June 1963.

9. Mard, K.C., "Comments on 'Effects of Control Loads on Fuselage VIbration' by D Kidd, et al", Journal of the AHS, Oct 67

10. Boeing Company Vertol Division. "Advanced Vibration Development (AVID) Program". Report 107MD09, April 1965.

11. Daughaday, Hamilton. "Suppresion of Transmitted Harmonic Rotor Loads by Blade Pitch Control". (Cornell Aeronautical Labratory, Inc.) U.S. Army Aviation Materiel Labratories, Fort Eustis, Virginia, TR 6714, November 1967, AD665430. Also see: Proceedings of the AHS, 23rd National Forum, Washington, DC, 1967.

12. Balcerak, J.C., and Erickson, J.C., Jr. "Suppresion of Transmitted Harmonic Vertical and Inplane Rotor Loads by Blade Pitch Control". (Cornell Aeronautical Labratory, Inc.) U.S. Army Air Mobility Research and Development Labratory, Fort Eustice, Virginia, TR6939, July 1969, AD960352.

13. Kretz, M., "Research in Multicyclic and Active Control of Rotary Wings". Proceeding of the First European Rotorcraft and Powered-Lift Forum, Southhampton, England, September 1975.

14. McCloud, J.L. III, Kretz, M. "Muticylic Jet-Flap Control for the Alleviation of Helicopter Blade Stesses and Fueslage Vibration". Proceedings of the NASA-Ames Specialist's Meeing on Rotorcraft Dynamics, NASA SP 352, February 1974.

15. Kretz,M., Aubrun, J.N., and Larche, M., "March 1971 Wind-tunnel Tests of the Dorand DH Jet flap rotor". NASA CR 114693 & 114694, 1973.

16. Kuczynski, W.A. and Sissigh, G.J., "Reasearch Program to Determine Rotor Response Charactatistics at High Advance Ratios", NASA CR 114290, LR 24122, February 1971.

17. Kuczynski, W.A. and Sissigh, G.J., "Charactaristics of Hingeless Rotors with Hub Moment Feedbadck Controls including Experimental Rotor Frequency response", NASA CR 114427 (Vol I) and NASA CR 114428 (Vol II), LR 25048, Janary 1972.

18. Kuczynski, W.A., "Experimental Hingeless Rotor Charactaristics at Full Scale First Flap Mode Frequencies", NASA CR 114519, LR 25491, October 1972.

19. London, R.J., Watts, G.A., and Sissingh, G.J., "Experimental Hingeless Rotor Charactaristics at Low Advance Ratio with Thrust", NASA CR 114684, December 1973.

20. McCloud, J.L. III, "An Analytical Study of a Multicyclic Controllable Twist Rotor", *AHS Proceedings*, 1975.

21. Kretz, M., "Relaxation of Rotor Limitations by Feedback Control", *AHS Proceedings*, May 1977.

22. McCloud, J.L. III, Weisbrich, A.L., "Wind-Tunnel Test Results of a Full-scale Multicyclic Controlable Twist Rotor", *AHS Proceeding*, May 1978.

23. Hammond, C.E., "Load Reduction Using Higher Harmonic Blade Pitch," *AHS Proceedings*, 1980.

24. Wood, E.R., Powers, R.W., Hammond, C.E., "On Methods for Application of Harmonic Control," Proceedings of the Fourth European Rotorcraft aand Powered-Lift aircraft Forum, Stresa, Italy, Sepptember 13-15, 1978 Paper No. 22 Also see *Vertica*, Vol. 4, No. 1, pp. 43-60 (1980)

25. Wood E.R., Power, R.W., "Practicle design considerations for a flightworthy Higher Harmonic Control System", *AHS Proceedings*, 1980.

26. Shaw, J.T., Albion, N., "Active Control of the Helicopter for Vibration Reduction." *AHS Proceedings*, 1980.

27. Ham, Norman D. and Quackenbush, Todd R., "A Simple System for Helicopter Individual-Blade-Control and Its Application to Stall-Induced Vibration Alleviation", American Helicopter Society National specialists' Meeting, Technology for the Jet Smooth Ride, Hartford, CT. Nov 2-4, 1981.

28. Chopra, I. and McCloud, J.L. III., "Considerations of Open-Loop, Closed-Loop, and Adaptive Multicyclic Control Systems", American Helicopter Society National specialists' Meeting, Technology for the Jet Smooth Ride, Hartford, CT. Nov 2-4, 1981.

29. Molusis, J.A. Hammond, C.E., Cline, J.H., " A Unified Approach to the Optimal Design of Adaptive and Gain Scheduled Controllers to Achieve Minimim Helicopter Vibration," Proceedings of the 37th AnnualForum of the American Helicopter Society, New Orleans, La., May 1981.

30. Wood, E.R., Platzer, M.F., Abourahma, A., Couch, M.A., "On the Unsteady Aerodynamics of Higher Harmonic Control," Ninteenth European Rotorcraft Forum, Paper no C17, Cernobio (Como), Italy September 14-16, 1993.

31. Polchroniadis, M., Achache, M., "Higher Harmonic Control: Flight tests of An Experimental System on SA 349 Research Gazelle," *AHS Proceedings*, 1986.

32. Miao, W., Kottapalli, S.B.R., Frye, H.M., "Flight Test Demonstration of Higher Harmonic Control (HHC) on S-76," *AHS Proceedings*, 1986.

33. Walsh, D.M., "Flight Tests of an Open Loop Higher Harmonic Control System on An S-76A Helicopter.", *AHS Proceedings*, 1986.

34. Shaw, J.T., Albion, N., Hanker, E.J. Jr., Teal, R.S., "Higher Harmonic Control: Wind Tunnel Demonstration of Fully Effective Vibratory hub Force Supression," *AHS Proceedings*, 1985.

35. Lehman, G., "The Effect of HHC to a Four Bladed Hingeless Model Rotor", *Vertica* 9, 273-284, 1985.

36. Shaw, J.T., Pizzini, G.B., Jervis, R.H., Teal, R.S., "Higher Harmonic Control Investigation of teh UH-60A Blackhawk Helicopter", U.S. Army Aviation Research and Technology Activity (USAAVSCOM), TM-86-D-4, April 1987.

37. Robinson, L.H., Friedmann, P.P., "Analytical Simulation of Higher Harmonic Control Using a New Aeroelastic Model", AIAA Paper 89-1321-CP, *Proc. AIAA/ASME/ASCE/ASCE/AHS Structures, Structural Dunamics and Materials Conference*, Mobile, AL, April 1989, Part I, pp. 1394-1406.

38. Robinson, L.H., Friedmann, P.P., "A Study of Fundemental Issues in Higher Harmonic Control Using Aeroelastic Simulation", *Proceedings of National Specialist's Meeting on Rotorcraft Dunamics*, Fort Worth, TX, Nov. 13-14, 1989.

39. Friedmann, P.P., "Helicopter Rotor Dynamics and Aeroelasticity: Some Key Ideas and Insights", *Vertica*, Vol. 14, No. 1, pp. 101-121, 1990.

40.Fenn, R.C., Goldie, J.H., Van Schoor, M.C.,"Harmonic Control and Actuation System", Naval Air Warfare Center SBIR Contract No. N00612-93-C-0204, SatCon Technology Corporation, Cambridge, MA, May 25, 1994.

41. Machine Design, "Smart Hush Helicopters", Machine Design, pp 36-38, August 8, 1994.

42. Sarigul-Klijn, M.M., "Application of Chaos Methods To Helicopter Vibration Reduction Using Higher Harmonic Control", Doctoral Dissertation, Naval Postgraduate School, Monterey, California, March, 1990.

43. Webb, C D., "Initial Design Study on Existin Flight Control System of RPH and Feasibility of Imlementing HHC on the SH-60B," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1990.

44. Abourahma, A. ,"The Analysis of Wake-Induced Unsteady Aerodynamics as related to Higher Harmonic Control" , Master's Thesis, Naval Postgraduate School, Monterey, California, December 1993.

45. Couch, M.A. "A Finite Wake Theory for Two-Dimensional Rotary Wing Unsteady Aerodynamics," Master's Thesis, Naval Postgraduate School, Monterey, California, September 1993.

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   Aerospace Engineering Department
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